ANALYSIS OF ON-RAMP CAPACITIES BY MONTE CARLO SIMULATION AND QUEUING THEORY

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by

R. F. DAWSON

Joint Highway Research Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

Final Report

ANALYSIS OF ON-RAMP CAPACITIES BY MONTE CARLO SIMULATION

AND QUEUING THEORY

TO: K. B. Woods, Director
Joint Highway Research Project

September 18, 1964

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File: 8-4-29
Project: C-36-17CC

Attached is a Final Report entitled "Analysis of On-Ramp Capacities by Monte Carlo Simulation and Queuing Theory" authored by Mr. Robert F. Dawson, Research Assistant on our staff. The research was performed under the supervision of Professor H. L. Michael and the report was also used by Mr. Dawson as his dissertation for the Ph.D. degree. Mr. Dawson performed the research while working for the degree under a loan from the Ford Foundation. As a result the cost to the Project of this research did not include any salary for the principal investigator.

The Plan of Study for this research was submitted to and approved by the Board at its January 7, 1964, meeting and this report completes the research proposed at that time. The report is presented for the record and for review and comments.

Respectfully submitted,

Harold L. Michael

Harold L. Michael, Secretary

HLM:bc

Attachment

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Final Report

ANALYSIS OF ON-RAMP CAPACITIES BY MONTE CARLO SIMULATION AND QUEUING THEORY

by

Robert Frank Dawson

Research Assistant

Joint Highway Research Project

File No: 8-4-29

Project No: C-36-17CC

Purdue University

Lafayette, Indiana

September 18, 1964

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ABSTRACT

Dawson, Robert Frank. Ph.D., Purdue University, January 1965. Analysis of On-Ramp Capacities by Monte Carlo Simulation and Queuing Theory. Major Professor: Harold L. Michael.

This research report is concerned with the analysis of the capacities of three different freeway on-ramp designs--namely, on-ramps with no acceleration lane and stop-sign control, on-ramps with no acceleration lane and yield-sign control, and on-ramps with an acceleration lane and no sign control. The study included the development of criteria for defining both possible and practical capacities, the development of a deterministic queuing model for predicting possible capacity, the development of a Monte Carlo simulation model for the study of ramp flow under varying traffic conditions, the evaluation of vehicle delays and queue lengths incurred by on-ramp vehicles for various combinations of ramp and shoulder-lane traffic volumes, and the evaluation of possible and practical on-ramp capacities for the three different ramp designs.

Initial research efforts were concerned with the development of descriptors of the ramp situation. The distribution of headways between ramp vehicles was described by a hyper-exponential model. All ramp vehicles were assumed to enter the ramp system

at a constant speed, controlled by the critical geometry of the area rather than by traffic. Ramp vehicle behavior in the system was defined by four factors--the spacing relationship with the preceding vehicle, acceleration-deceleration capabilities, the availability of gaps in the shoulder lane, and distributions describing gap-acceptance phenomena.

Shoulder-lane headways were described by a shifted-exponential model. Each shoulder-lane vehicle was assigned a speed upon entry into the system that was only dependent upon the volume of traffic in the shoulder lane. It was further assumed that the shoulder-lane vehicles proceeded through the ramp area at the speeds and headway spacing assigned at generation, without any interference from ramp traffic.

The various traffic descriptors were expressed in the mathematical mode and assembled for analysis into two different types of models--a deterministic queuing model for the analysis of possible ramp capacity, and a Monte Carlo simulation model for the analysis of practical capacity.

Because both models were constructed in the mathematical mode they were readily programmed for computer solution. The programs were coded in the FORTRAN IV and MAP languages for the IBM 7090/7094 System and were run on an IBM 7090.

The results obtained from the queuing-model analysis were reported in graphical form. The possible capacities of each of the three ramp designs were plotted as functions of shoulder-lane volume. Delay and queuing characteristics for a wide range of ramp and shoulder-lane volume combinations were obtained from

the simulator. Practical capacities were defined for each of the three ramp designs by analyzing the delay characteristics relative to the criteria established for practical capacity in the definition of the same. Queue storage requirements on the ramp were found by an analysis of queuing characteristics at practical-capacity volume levels.

INTRODUCTION

In recent years thousands of miles of freeway-type highways have been constructed to provide for the safe, convenient and efficient transportation of persons and goods. Access to these high-type traffic-carrying facilities is provided by on-ramps that are designed to merge ramp traffic into the high-speed, high-volume traffic stream. The efficiency of traffic movement on freeways, and the extent to which the potential capacity of freeways can be realized, depends in part on the adequacy of the access facilities. Improperly designed entrances limit the volume of traffic that can use an expressway and generate congestion that often extends back onto the local system.

Purpose and Scope of Study

The purpose of this study was four-fold:

1. To develop criteria for defining possible and practical on-ramp capacities;

2. To develop general models for the analysis of flow through the merge area;

3. To evaluate vehicle delays and queue lengths that are incurred by on-ramp vehicles for various combinations of freeway and ramp volumes; and

4. To define the possible and practical capacities of freeway on-ramps for each of three design-control situations.

Freeway on-ramp capacity is controlled at one or more of three locations along the typical ramp. These locations are--(1) the entrance to the ramp from the local system or another freeway, (2) the ramp proper, and/or (3) the merge area at the freeway terminal of the ramp. This study was devoted to an analysis of the latter location, the merge area at the freeway terminal, as it is more commonly the restricting element of the ramp.

Only ramps with geometric configurations such that on-ramp merge maneuvers are not compounded with off-ramp diverge maneuvers were considered. Thus the analysis is pertinent to the on-ramps of diamond interchanges and to the outer-loop connectors of cloverleaf interchanges. The typical ramp-terminal designs and controls which are used on existing freeways were analyzed and compared--no acceleration lane with stop-sign control, no acceleration lane with yield-sign control, and an acceleration lane with no sign control. The layouts assumed for these control situations are shown in Figure 1 for no acceleration lane with stop-or yield-sign control and in Figure 2 for an acceleration lane with no sign control.

The conduct of a field study of the scope proposed was impractical with respect to both cost and time. In addition data from numerous traffic studies of existing access facilities located throughout the country were already available. The

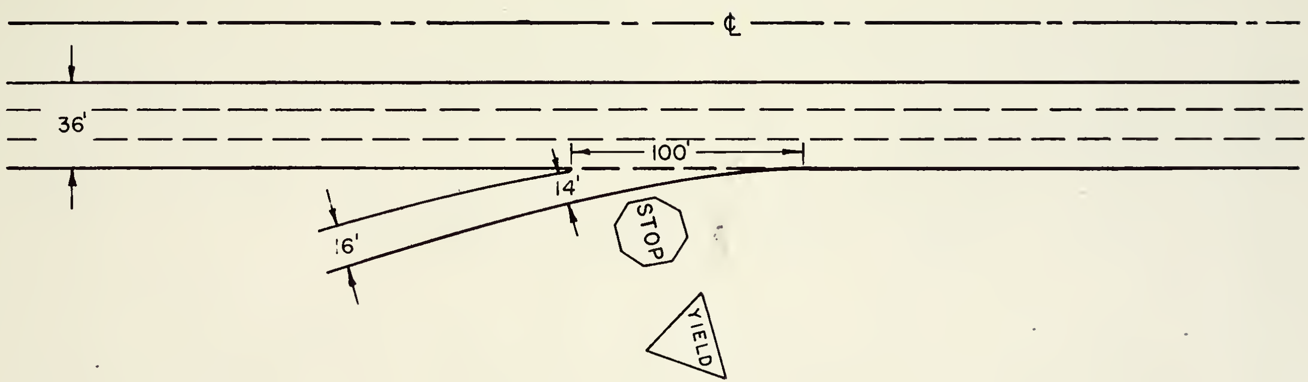

FIG. 1 - TYPICAL STOP-SIGN OR YIELD-SIGN CONTROLLED FREEWAY ON-RAMP WITHOUT ACCELERATION LANE

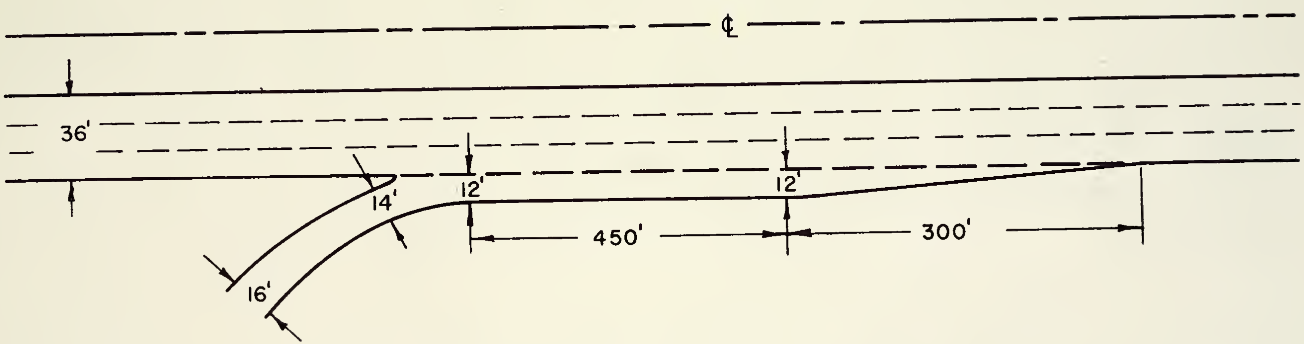

FIG. 2 - TYPICAL FREEWAY ON-RAMP WITH ACCELERATION LANE AND NO-SIGN CONTROL

existence of these data, plus the availability of a modern high-speed digital computer, suggested the development of simulation and queuing models for analyzing ramp capacity.

CRITERIA FOR ON-RAMP CAPACITY

The term "capacity," as it is applied to highway traffic facilities, is not uniquely descriptive. In general, it pertains to the ability of a facility to accommodate traffic; but without some criteria indicative of the level of performance associated with a volume of flow, the statement of a numerical capacity limit is incomplete.

Two variables, commonly considered as yardsticks of performance, are vehicle delay and queue length. Vehicle delay can be expressed in terms of the average delay incurred by a vehicle for various combinations of ramp and freeway volumes, or as the probability that delay exceeds some established level. Queuing characteristics can be defined by the mean queue length, or in terms of some percentile value such as the 85th, 90th, or 95th percentile queue length. Although definite limits should be established for the delay indices, there is no reason to establish numerical limits for general application in the case of queues. A design engineer should merely use defined queuing characteristics to establish storage requirements for ramp traffic, when the ramp is operating at a capacity level established relative to delay characteristics.

In an attempt to establish a uniform capacity concept the American Association of State Highway Officials (1)* adopted definitions of highway capacity at two levels of performance. These definitions follow:

> "Practical Capacity represents the maximum number of vehicles that can pass a given point on the lane or roadway during one hour under the prevailing roadway and traffic conditions, without unreasonable delay or restriction to the driver's freedom to maneuver."

> "Possible Capacity is the maximum number of vehicles that can pass a given point on a lane or roadway during one hour under the prevailing roadway and traffic conditions, regardless of their effect in delaying drivers and restricting their freedom to maneuver."

Although these definitions were intended for uninterrupted traffic facilities, the rationale can be applied to ramp situations. In addition, the Highway Capacity Manual (2) definitions for capacities of signalized intersections suggested an index for describing reasonable delay. These definitions state:

> "The Practical Capacity of an intersection approach under signal control is the maximum volume that can enter the intersection from that approach during one hour with most of the drivers being able to clear the intersection without waiting for more than one complete signal cycle."

> "Possible Capacity is the maximum number of vehicles that can actually be accommodated under the prevailing conditions with a continual backlog of waiting vehicles."

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* Numbers in parentheses refer to entries in the List of References.

Two modifications to the practical capacity definition were necessary before it was applicable to the ramp situation. The first modification involved the number of drivers being delayed. The qualitative index "with most of the drivers being able to clear the intersection" was replaced by the quantitative index "with 85 percent of the drivers being able to clear the intersection." The second modification involved the length of delay incurred by the drivers. Since signals are not commonly used for traffic control on on-ramps the time unit "one signal cycle" was replaced by an approximately equivalent time period of "60 seconds." The definition proposed for the practical capacity of a freeway on-ramp is as follows:

> The practical capacity of a freeway on-ramp is the maximum volume of vehicles that can enter the through highway during one hour with 85 percent of the drivers being able to leave the ramp without being delayed for more than 60 seconds.

The definition of the possible capacity of a signalized intersection was applicable to the ramp situation without modification.

Another consideration that should not be overlooked involves the effect that traffic from the ramp might have on shoulder-lane traffic flow. A ramp volume that forces the shoulder-lane volume above the capacity of the lane can hardly be considered to be within the capacity of the ramp. In other words if a ramp capacity, determined in accordance with the proposed definitions, causes the volume downstream from the intersection area to exceed the capacity of the lane, the calculated capacity

should be disregarded. In such a case the capacity should be reported as the difference between the capacity of the shoulder lane and the actual volume being carried in the shoulder lane.

As an alternative it would be reasonable to consider the volumes in all lanes downstream of the merge area. If the total volume carried in all lanes downstream of the merge area exceeds the capacity of the available number of lanes, it would be necessary to reduce the ramp capacity to a value such that the sum of the volumes of all lanes approaching the merge area, plus the merging ramp volume, does not exceed the sum of the capacities of all lanes.

REVIEW OF ON-RAMP CAPACITY

Variables Influencing Ramp Capacity

The capacity of a freeway on-ramp is affected by the three basic elements of a traffic system--the roadway, the vehicle, and the driver-- as well as by the traffic and environmental conditions that prevail. Each of these influencing elements can be further subdivided. Roadway character is fully described by geometric aspects such as lane width, gradient and curvature, by geometric design of the acceleration lane (primarily length), and by the type of control (stop-sign, yield-sign, or no sign control).

Vehicle characteristics that are of concern in the analysis of on-ramp capacity are primarily the length of the vehicle and the acceleration-deceleration potential of the vehicle. In most cases the acceleration-deceleration characteristics are not critical due to the fact that driver comfort requirements usually control.

Driver characteristics are very important in the analysis of on-ramp capacity. The reaction time of a driver affects his ability to maintain a constant position in a stream and to take advantage of merging opportunities. The acceptance of gaps in the shoulder-lane stream, a phenomenon having direct effect on ramp capacity, follows a probability distribution, instead of

being constant, due to variation between and within ramp vehicle drivers. This variation is accounted for in part by the minimum headways that a driver demands in a stream, and by the maximum acceleration-deceleration rates that a driver desires to use.

The influence of traffic environmental conditions on the capacity of on-ramps cannot be overlooked. The potential excess capacity of the shoulder lane is directly related to the volume, speed and composition of the freeway stream, whereas the ability of the ramp stream to utilize this excess capacity is a function of its own volume, speed and composition.

Procedures For Analysis of On-Ramp Capacity

At least four different techniques for predicting freeway on-ramp capacities have been reported in the literature. These techniques are briefly defined by the author as the "shoulder-lane capacity-volume" approach; the "regression model prediction" approach, the "shoulder-lane gap-use" approach, and the "simulation" approach.

In regard to the first of these techniques the Highway Capacity Manual (2) suggests that it is common practice to define the capacity of an on-ramp as the difference between the capacity of the freeway and the traffic volume on the freeway ahead of the ramp. It does point out, however, that such a capacity could only be achieved when the unused capacity is available in the shoulder lane. This latter concept is presented

in equation form in the AASHO Policy on Geometric Design of Rural Highways (1) with additional adjustments for the percentages of trucks in the shoulder lane, and ramp traffic streams. The expression for the practical capacity of a single lane entrance with an acceleration lane and no sign control is given as,

$$C_{r_2} = \frac{C_{s_2} - V_s (1 + t_s)}{1 + t_r} ,$$

where :

C_{r_2} = practical capacity of ramp, vph;

C_{s_2} = practical capacity of shoulder lane, vph;

V_s = actual through volume in shoulder lane, vph;

t_s = trucks in shoulder lane expressed as percentage of total lane volume divided by 100; and

t_r = trucks on ramp expressed as percentage of total ramp volume divided by 100.

The truck corrections are based on an assumption that each truck is equivalent to two passenger cars.

More recent research by Moskowitz and Newman (13) in California was devoted to the refinement of this capacity-volume approach to the definition of on-ramp capacities. Their results generally pertain to situations in which the on-ramp merging maneuver is compounded with a following off-ramp diverging maneuver; however, when the distance to the following off-ramp is long enough the on-ramp is essentially an isolated merging

area. The major contributions of this research were graphical models for the prediction of shoulder-lane volume as a function of several variables--the number of lanes per direction of flow, the total freeway volume, the distance upstream to the last on-ramp, and the distance downstream to the next off-ramp. Moskowitz cautions that previous to the application of the proposed method of analysis the ramp area should be checked to insure that:

1. The rate-of-flow in the shoulder lane does not exceed 1800 vph;
2. The number of weaving vehicles does not exceed 2100 vph in any 500-foot segment of the weave section; and
3. The average rate-of-flow across all lanes does not exceed 1800 vph per lane.

Results from another recent freeway capacity study conducted under the auspices of the Bureau of Public Roads have been reported by Hess (4). The regression model prediction techniques presented as a consequence of this comprehensive study departed from the capacity-volume concept. Two multiple regression models were developed to predict a so-called free-flow merge capacity for one-lane on-ramps where a free-flow merge is defined by Hess as a merge under a

> "condition where freeway traffic is moving in a uniform manner somewhere in the 35- to 60-mph range. Large fluctuations in speed are few and traffic is experiencing no conflicts severe enough to cause intermittent braking or congestion. Ramp traffic flow, though possibly slower in speed than the freeway, is continuous without backing on the ramp. The merge of

> the two streams is normally smooth within the usual adjustments in speed necessary for this maneuver. No specific overall speed should be associated with "free flow," as the design and type of interchange will have an important effect on the speed at any one location. The free-flow periods chosen for this study are of 15-minute duration and these volumes are expanded to one hour by multiplying by four (15-minute f.f. exp.) The operation during a free-flow period is assumed to be capable of continuance, barring increasing demand, backup from downstream, or vehicular accidents. Yet volumes will be in the practical to possible capacity ranges so that increased demand could cause a breakdown in the operation."

Free-flow ramp capacity is defined as the difference between free-flow merge capacity and shoulder-lane volume. The first of the regression models, that are given below for the prediction of the free-flow merge capacity, was derived from data obtained at 73 various locations and can be applied to all types of interchanges except left-hand connections. A second model was obtained by dropping from the analysis 18 locations with short ramps or with sharp curvature near the ramp nose. These models were presented as follows:

$$Y_1 = 528 + 8.5X_1 - 16.5X_2 + 7.6X_3 - 1.0X_4 + 0.22X_5 + 0.071X_6;$$

and

$$Y_2 = 441 + 10.0X_1 - 18.0X_3 + 9.5X_3 - 5.0X_4 + 0.014X_5 + 0.68X_6;$$

where the dependent variables are defined as:

Y_1 = free-flow merge (vph) based on model derived from data collected at 73 ramp locations, and

Y_2 = free-flow merge (vph) based on model derived from data collected at 55 ramp locations.

The independent variables were defined as follows:

X_1 = percent freeway utilization

$$= \frac{\text{Freeway Volume (vph)}}{\text{No. of lanes x 2000 vph/lane}} \times 100;$$

X_2 = percent commercial vehicle in merge

$$= \frac{\text{C.V. (Ramp + Shoulder lane) vph}}{\text{Expected merge volume (vph)}} \times 100;$$

X_3 = ramp/merge ratio

$$= \frac{\text{Ramp Volume (vph)}}{\text{Expected merge volume (ramp + shoulder lane) vph}} \times 100;$$

X_4 = angle of convergence (degrees)

= the interior angle between the right edge of the shoulder lane and the left edge of the ramp;

X_5 = length of acceleration lane (feet); and

X_6 = metropolitan area population (1000's), with a maximum value of 5000 being used in the formula.

Hess reported multiple R^2's of 0.68 and 0.71, thus indicating that the prediction models explained 68 and 71 percent of the variation in the 73- and 55-location data sets, respectively. The associated coefficients of variation were 0.108 and 0.098.

The third method for the analysis of on-ramp capacities, the shoulder-lane gap-use technique, was proposed in the Highway

Capacity Manual (2) for analysis of possible capacity. This method involves predictions of the shoulder-lane volume, of the number and sizes of gaps between vehicles in the shoulder lane (time spacings from front bumper to front bumper of contiguous vehicles), and of the number of ramp vehicles that will use each shoulder gap in the shoulder-lane stream assuming a continuous backlog of vehicles on the ramp. It can be summarized mathematically as,

$$C_{r_1} = \sum_{T_i=T_{min}}^{T_{max}} V_s \times P(T_i) \times N(T_i) ,$$

where:

C_{r_1} = possible ramp capacity (vph);

T_i = any gap time interval (sec);

T_{min} = shortest gap time interval acceptable (sec);

T_{max} = longest gap time interval possible in a stream (approaches ∞) sec;

$P(T_i)$ = proportion of total number of gaps in a stream that fall in the size range, T_i; and

$N(T_i)$ = average number of vehicles that can use a gap of length, T_i, when the queue on the ramp is long enough to insure that the entire gap will be used at the discretion of the ramp vehicle driver (vehicles).

Although this model is presented specifically for the analysis of ramps with no acceleration lane and stop-sign control it is

appropriate for the analysis of all other types of on-ramp designs provided the necessary data is available.

Pearson and Ferreri (16) also reported the results of a study of the possible capacities of on-ramps located on the Schuylkill Expressway in Philadelphia using the gap-use technique of analysis. Lane-distribution and gap-use data were obtained directly from traffic studies conducted on the Schuylkill Expressway. The shoulder-lane gaps were assumed to follow a negative-exponential distribution such that the proportion of gaps in any given interval were determined from the following mathematical model:

$$P(T_i) = e^{-\gamma t_l} - e^{-\gamma t_u} ,$$

where:

T_i = any given gap interval;

$P(T_i)$ = proportion of total number of gaps in the stream that fall into the interval, T_i;

γ = average flow rate of vehicles in the shoulder lane (vehicle/second);

t_l = the lower limit of the gap interval, T_i (sec); and

t_u = upper limit of T_i (sec).

The final technique for the analysis of freeway on-ramp capacities, the simulation technique, is relatively new to the highway traffic field. Simulation has been described by Harling (9) as "the technique of setting up a stochastic model of a real system which neither over-simplifies the system to the point

where the model becomes trivial nor incorporates so many features of the real system that the model becomes untractable or prohibitively clumsy." Basically a ramp simulation model is the abstraction of the ramp system--including the roadway, the vehicle, the driver, and the traffic and environmental conditions--into a mathematical form. The dynamic solution of the inter-related components of the model on a high-speed digital computer effects the simulation of the abstracted system. As vehicles are introduced into the system, moved through the system in a manner dictated by the rules of operation, and exited from the system, each of the desired characteristics is recorded. The successive processings by which these operations are effected can be scheduled either at uniform increments of time or at critical times. If they are scheduled at uniform time increments the simulated system is scanned at the end of set time periods--for example, every one-half second--and the vehicles advanced the appropriate distance for that time period. If the processings are scheduled at critical times the system is only scanned at those points in time in which significant events, such as ramp vehicle arrivals or departures, occur.

At least two simulation models prepared for the analysis of on-ramp situations, have been reported. The first of these models, a uniform time increment simulator, was prepared for the analysis of ramp areas with compounded on-off movements by Findley, Levy, Glickstein, and Perchonok (7, 8, 9, 10) of the Midwest Research Institute in cooperation with the Bureau of Public Roads. It

was structured in such a manner that it required the following inputs describing the situation to be simulated:

1. The volume of entering and exiting vehicles,
2. The distribution of vehicles between lanes,
3. The velocity distribution of vehicles,
4. The gap-acceptance distribution of merging and weaving vehicles,
5. The acceleration rate of entering vehicles,
6. The deceleration rate of exiting vehicles, and
7. The distribution of exiting vehicles between lanes.

This simulator, which was programmed for the IBM 704 digital computer, returned output describing:

1. The volume of vehicles traversing the system in each lane,
2. The volume of vehicles entering the freeway from each on-ramp,
3. The volume of vehicles leaving the system at each off-ramp,
4. The number of vehicles stopping on the acceleration lane,
5. The lengths of queues on the ramp,
6. The number of vehicles desiring to leave the system that cannot,
7. The distribution of through-vehicle traverse times,
8. The distribution of ramp-vehicle times,
9. The average velocities by lanes, and

10. The number of weaves occurring between adjacent through lanes.

The second ramp simulator, prepared by Wohl (19, 20), was designed as a critical period simulator and was programmed for the IBM 704. Although Wohl did not completely describe the simulator inputs they undoubtedly included shoulder-lane volume and headway distribution, ramp volume and headway distribution, and gap-acceptance data. Output from simulation runs made at various combinations of ramp and shoulder-lane volumes consisted of ramp-vehicle delay data which could be used as a criteria for the establishment of levels of ramp capacity.

Results of Previous Studies

The results of on-ramp capacity analyses by various techniques, as they were obtained from the literature, were compared in accordance with the on-ramp design and/or the types of traffic control. Comparisons were made between:

1. The possible capacities of on-ramps with no acceleration lane and stop-sign control as defined by capacity-volume and gap-use techniques;
2. The possible capacities of on-ramps with acceleration lanes and no sign control as defined by the same two techniques; and
3. The free-flow merge capacities of on-ramps on diamond interchanges and on the outer-

connectors of clover-leaf interchanges, as defined by the regression prediction model technique.

The results from the various studies were converted to a common format for comparison. The format selected was ramp capacity versus shoulder-lane volume. In making such a conversion the significance of some of the capacity-volume analysis techniques was lost as part of each of these analysis techniques was the prediction of traffic distribution between lanes.

No Acceleration Lane and Stop-Sign Control

The possible capacities obtained from the previous studies as noted above for on-ramps with no acceleration lane and stop-sign control are compared in Figure 3. These results are obviously inconsistent. The solid-line curve obtained from data in the Highway Capacity Manual (2), using the shoulder-lane capacity-volume analysis technique, is based on a shoulder-lane capacity of 1800 vehicles per hour and undoubtedly predicts ramp capacities that are too high. Although the curve represents a real excess capacity potential in the shoulder lane, ramp vehicles cannot and/or will not accept the available gaps in such a manner as to utilize all of the excess capacity.

The results of an analysis by the gap-use technique, also obtained from the Highway Capacity Manual, are represented by the dashed line of Figure 3. Again discussion is warranted. It

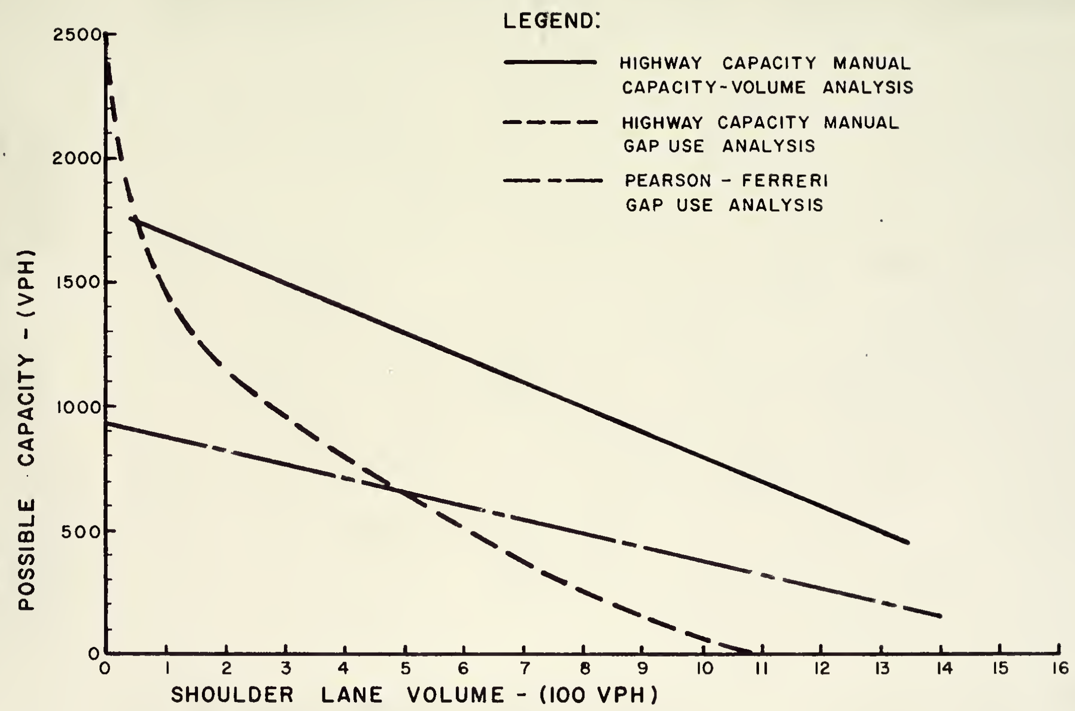

FIG. 3 - COMPARISON OF POSSIBLE CAPACITIES OF FREEWAY ON-RAMPS WITH NO ACCELERATION LANE AND STOP-SIGN CONTROL OBTAINED FROM VARIOUS RESEARCH STUDIES

is highly unlikely that successive vehicles could depart from a stop-sign controlled ramp with headways much shorter than four seconds, if they complied with the intent of the stop sign. Assuming that vehicles could exit from the ramp with average headway of four seconds, a maximum ramp capacity of 900 vehicles per hour could be realized with no vehicles in the shoulder lane. The low capacities indicated by this technique at higher shoulder-lane volumes are also questionable. At a shoulder-lane volume of 1100 vehicles per hour the Highway Capacity Manual indicates that 30 percent, or 330, of the gaps in the shoulder are longer than five seconds and that as many as four percent, or 44 gaps, are in excess of ten seconds in length. Without question there is excess capacity in the shoulder lane that the ramp driver can and will use. The curve (See Figure 3), however, indicates zero capacity for shoulder-lane volumes of 1100 or more vehicles per hour.

The final curve shown in Figure 3 was recently derived by Pearson and Ferreri (16) using the shoulder-lane gap-use technique with data collected on the Schuylkill Expressway in Philadelphia. Although their model does not have the objectionable features contained in the previous model, several aspects warrant discussion. Pearson and Ferreri defined the results of their analysis as practical capacity, whereas a review of their procedures indicates that they have really derived possible capacities for the various shoulder-lane volume conditions. The procedure involved a determination of the number of gaps in each

size range for an indicated shoulder-lane volume; and calculation of the average number of vehicles that use each gap size, assuming of course that there are at least as many vehicles queued on the ramp as the gap-acceptance model predicts will use a gap. It is apparent that the delays that would result from the long traffic backlogs are not reasonable. Because the delays are not reasonable and because a continual backlog of vehicles on the ramp is required, the resulting capacities are possible capacities.

A second point of concern involves the average gap-use model developed by Pearson and Ferreri. The model was of a linear, two-space form,

$$N(t_i) = -1.07 + 0.281t \quad ,$$

where:

t_i = size of available gap in the shoulder-lane stream, and

$N(t_i)$ = average number of vehicles that will use a gap of size, t_i sec.

Although this model should be linear with changes in gap length for all gaps in excess of that length for which the probability of acceptance is one, it cannot be linear for changes in gap length in the gap-size range where probabilities of acceptance are less than one. In this range the model must follow a form that generates a curve that is convex-upward. At higher shoulder-lane volumes most of the available gaps fall in the

non-linear range of the curve with the result that average gap use is lower than that predicted by the linear model.

A third point of interest developed as a consequence of programming and running the gap-use analysis technique on an IBM 7090 digital computer. The possible capacity model that was obtained using Pearson's data as inputs for the analysis was found to be perfectly linear when transformed to a semi-log form as shown in Figure 4. The original model, however, was given in a linear form with rectangular coordinates. This indicates that Pearson and Ferreri failed to select the best functional form to fit to their data.

Further research in an attempt to find a reason for the linear log transformation brought forth a fourth and final point of interest. It was found that the transformed log model could be derived as a rational and theoretically sound queuing model (15). The necessary assumptions were the same as those made by Pearson and Ferreri--namely, that shoulder-lane headways follow a negative-exponential distribution and that average gap use is linear with respect to gap length. Since shoulder-lane headways follow a negative-exponential distribution, the portion of the headways that exceed any length, t_i, is $e^{-\gamma t_i}$ where γ is the average rate of traffic flow in the stream. The portion of headways between vehicles that exceed t_j, where t_j is any length greater than t_i, is $e^{-\gamma t_j}$. Hence the portion of the headways between shoulder-lane vehicles that lie between t_i and t_j is $(e^{-\gamma t_i} - e^{-\gamma t_j})$. Since the total number of gaps in a

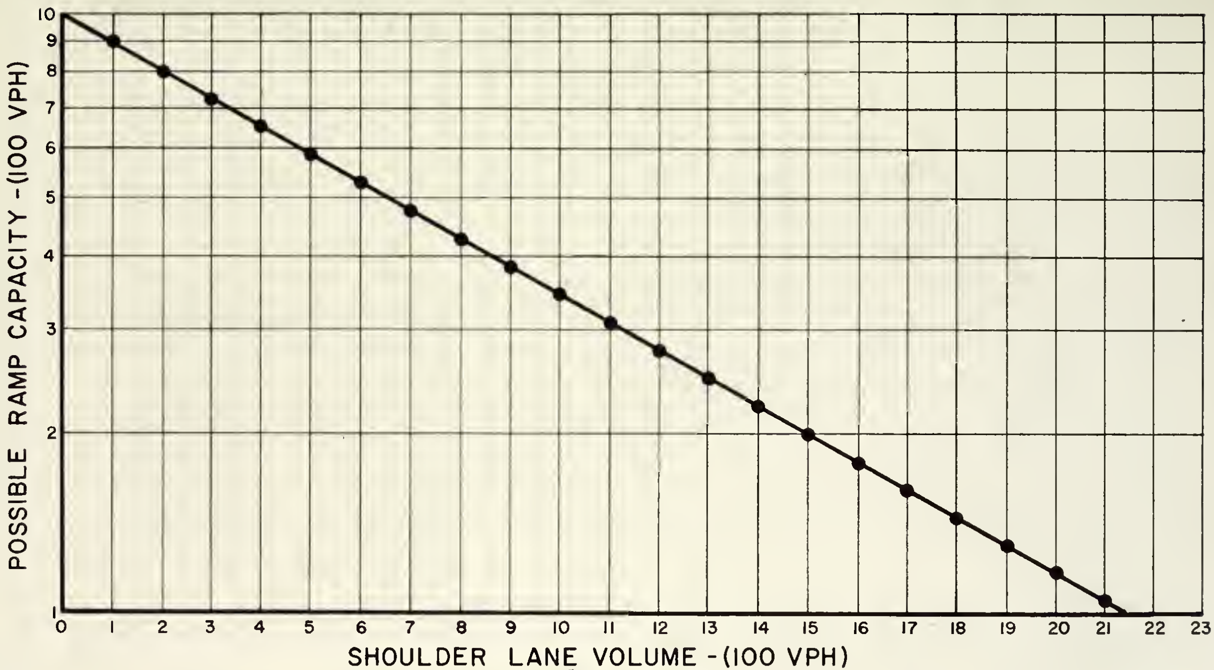

FIG.4 - POSSIBLE CAPACITY OF ON-RAMP WITH NO ACCELERATION LANE AND STOP-SIGN CONTROL OBTAINED USING GAP USE TECHNIQUE AND PEARSON'S DATA

stream for any time period is equal to the flow volume for that period, the number of gaps that fall in the range $t_i - t_j$ is $V(e^{-\gamma t_i} - e^{-\gamma t_j})$. Further development of the queuing models is dependent upon Pearson's average gap-use curve presented in Figure 5. Three significant limiting gap times are indicated in the Figure. These are:

1. t_1 - the minimum shoulder-lane gap acceptable to a ramp vehicle,
2. t_2 - the lower limit of a gap range that on the average will accommodate one ramp vehicle, and
3. t_3 - the time increment required by each additional ramp vehicle.

It is assumed that the gaps falling between the limits of t_1 and t_2 will accommodate 0.25 vehicles on the average. The queuing model for possible capacity can now be derived by determining the number of gaps in each time interval, multiplying each of these numbers by the average number of gap users per gap, and summing the results. This procedure is developed mathematically as follows:

$$
\begin{aligned}
C_{r_1} = V_s \Big[& 0\left(1 - e^{-\gamma t_1}\right) + 0.25\left(e^{-\gamma t_1} - e^{-\gamma t_2}\right) \\
& + 1\left(e^{-\gamma t_2} - e^{-\gamma (t_2 + t_3)}\right) \\
& + 2\left(e^{-\gamma (t_2 + t_3)} - e^{-\gamma (t_2 + 2 t_3)}\right) \\
& + 3\left(e^{-\gamma (t_2 + 2 t_3)} - e^{-\gamma (t_2 + 3 t_3)}\right) \\
& + \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \Big],
\end{aligned}
$$

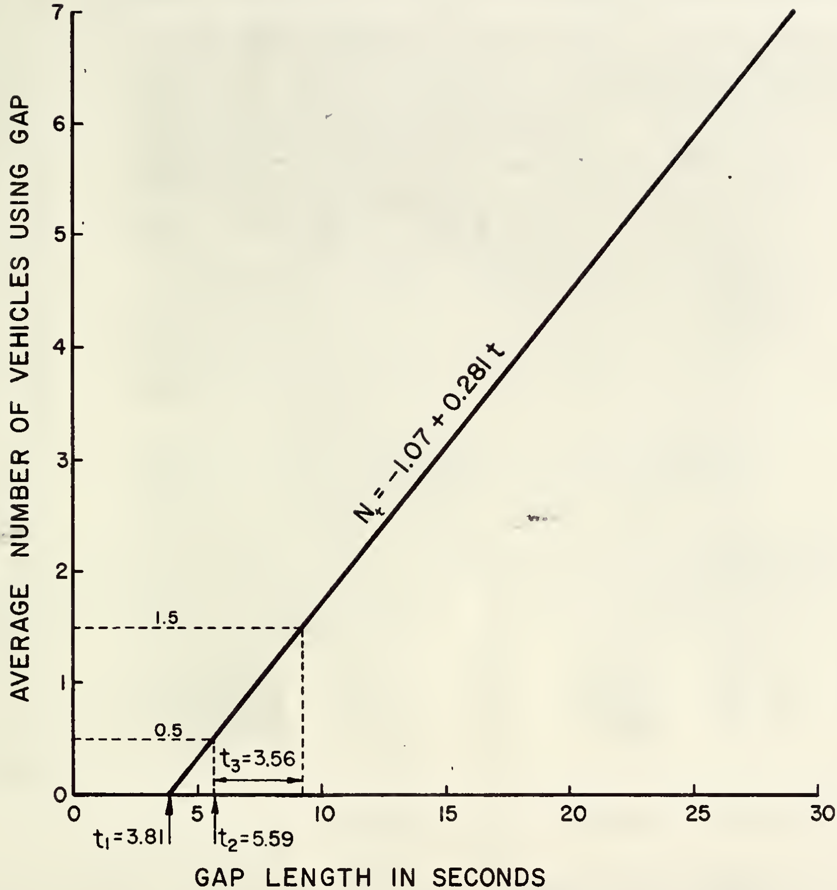

FIG. 5 - AVERAGE GAP-USAGE MODEL FOR STOP-SIGN CONTROLLED ON-RAMPS PROPOSED BY PEARSON AND FERRERI

$$C_{r_1} = V_s \Big[0.25 \left(e^{-\gamma t_1} - e^{-\gamma t_2} \right)$$

$$+ e^{-\gamma t_2} \left(1 + e^{-\gamma t_3} + e^{-2\gamma t_3} + e^{-3\gamma t_3} + \ldots \right) \Big],$$

$$C_{r_1} = V_s \left[0.25 \left(e^{-\gamma t_1} - e^{-\gamma t_2} \right) + e^{-\gamma t_2} \left(1 - e^{-\gamma t_3} \right)^{-1} \right],$$

where:

C_{r_1} = possible ramp capacity (vph);

V_s = shoulder lane volume (vph);

γ = unit flow rate of shoulder-lane stream expressed in whatever unit of time is used for t_1, t_2, and t_3; and

t_1, t_2, and t_3 are as defined previously. With the appropriate substitutions,

$$C_{r_1} = V_s \left[0.25 \left(e^{-3.812\gamma} - e^{-5.59\gamma} \right) + e^{-5.59\gamma} \left(1 - e^{-3.562\gamma} \right)^{-1} \right],$$

where:

$$\gamma = V_s / 3600.$$

Acceleration Lane and No Sign Control

The possible capacities of on-ramps with acceleration lanes and no sign control are compared in Figure 6. The solid curve, defined by the Highway Capacity Manual (2) capacity-volume

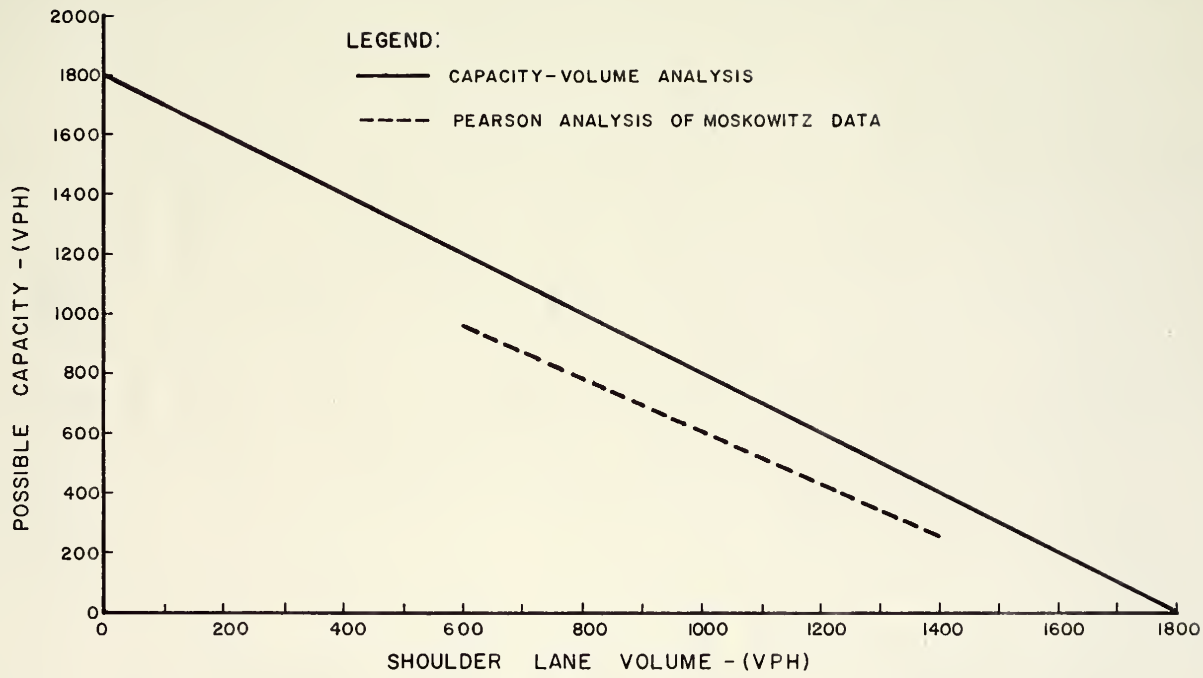

FIG. 6 - COMPARISON OF POSSIBLE CAPACITIES OF FREEWAY ON-RAMPS WITH ACCELERATION LANES AND NO SIGN CONTROL OBTAINED FROM VARIOUS RESEARCH STUDIES

analysis technique, is based on a shoulder-lane capacity of 1800 vehicles per hour. Since this technique does not consider the relative facility with which the ramp stream can utilize excess shoulder-lane capacity there is no distinction between the possible capacities of on-ramps with different geometric and traffic control designs. There would be a distinction, however, if ramp capacities were plotted as a function of total one-way freeway volume. This distinction would result from the fact that traffic distribution between lanes varies with the geometry and/or type of control on the on-ramp.

The dashed possible-capacity curve of Figure 6 was defined by Pearson and Ferreri (16) from data obtained in an early ramp capacity study by Moskowitz (14). It is apparently based on the capacity-volume analysis technique, but shoulder-lane capacity varies in the ramp area--decreasing slightly as the percentage of ramp traffic in the shoulder-lane immediately downstream of the merge area increases.

Diamond and Outer Cloverleaf Connector On-Ramps

Free-flow capacities are presented in Figure 7 for on-ramps located at diamond interchanges and on the outer connectors of cloverleaf interchanges. These capacity curves were derived by Moskowitz and Newman (13) by determining the varying combinations of ramp and shoulder-lane volumes that effect free-flow merge capacities. As there was scatter in the generated data, best-fit curves were established by the method of least-squares.

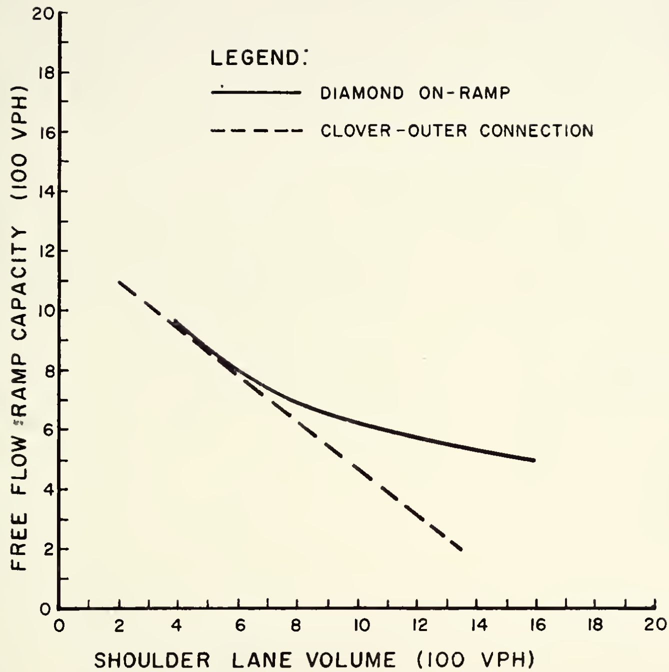

FIG. 7 - FREE-FLOW CAPACITIES OF FREEWAY ON-RAMPS (FROM J.W. HESS)

The resulting equations for the diamond on-ramp and for the outer cloverleaf connection were, respectively:

$$C_r = 17.029\ V_s^{-0.479}$$

and

$$C_r = 1257 - 0.79V_s\ ,$$

where:

C_r = free-flow ramp capacity (vph), and

V_s = shoulder-lane volume (vph).

No coefficients of determination were given for these fits.

DESCRIPTORS OF THE RAMP SITUATION

The place and geometry of the ramp area is established by design, but the maneuvers within the ramp area are combinations of random processes modified by regulation and control and of course by the design. While in the vicinity of the ramp area, drivers must coadjust, modifying both speed and path as they traverse the area to a local destination.

Although there are many variables involved in the operation of the ramp area traffic system all of them can be classified under five headings--roadway characteristics, vehicle characteristics, driver characteristics, traffic and environmental conditions, and rules of operations.

Roadway Characteristics

Geometric Layout

The two on-ramp geometric layouts analyzed in this study were presented in Figures 1 and 2. The dimensions assumed for the no acceleration-lane design were based on a survey of plans of existing facilities including the Congress Avenue Expressway in Chicago, the Schuylkill Expressway in Philadelphia, and the Merrit and Wilbur-Cross Parkways in Connecticut. Although no exact locations were defined for the entry point to the system,

for the stop-line, or for the point of entry into the shoulder-lane, the proposed design was adequate to provide 108 feet for deceleration from ramp speed to a stop at the stop-line. In addition the assumption was made that the vehicle traveled a distance of 92 feet from the stop-line to the point of entry into the shoulder lane.

The dimensions for the acceleration-lane design were based on a survey of recommended ramp designs. With a 450-foot acceleration-lane proper and a 300-foot taper, ramp vehicles had approximately 500 feet of acceleration distance available before encroaching on the shoulder-lane. This distance was just adequate to provide for acceleration from a stop at the ramp nose to the maximum average shoulder-lane speed. Again the ramp geometry was adequate for the driver to decelerate from the ramp speed to a stop at the ramp nose with a comfortable rate of deceleration when such a maneuver was deemed necessary.

Traffic Control

Three separate traffic-control conditions were analyzed. Both stop-sign and yield-sign control devices were established on the no acceleration-lane layouts; no sign control was established on the acceleration-lane layout. Results reported from previous research studies indicated that stop-sign control devices on ramps often function as yield signs or as a cross between a stop-sign and a yield-sign. For the purposes

of this study each device was required to function in compliance with the regulations defined in the Manual on Uniform Traffic Control Devices.

Vehicle Characteristics

All of the vehicles traversing the ramp system, whether on the ramp or on the shoulder lane, were assumed to have the geometric and operating characteristics of passenger cars. Overall length was established at 16.5 feet, the approximate average for all passenger cars, although this is considerably shorter than the AASHO defined P design vehicle (1).

In addition each vehicle was assigned constant acceleration and deceleration potentials of five and six miles per hour per second, respectively. In reality acceleration and deceleration rates have distributions that are functions of the vehicle, the driver, the roadway, and the environment; but because of inadequate data and for simplicity, these variables were defined as constant vehicle characteristics.

Driver Characteristics

PIEV Time

Although the driver is probably the most complex and certainly the dominant element in the ramp traffic system he was modeled as a relatively simple machine with a capability for completing the "PIEV" process in 1.5 seconds. Although it is known that perception, intellection, and volition time

requirements, under emotional stress, vary among and within drivers, as well as among situations, lack of information on this distribution led to the selection of the above average, and hopefully, representative constant time.

Minimum Time and Space Clearances

The minimum time and space clearances that a driver demands as a buffer between himself and a lead vehicle are undoubtedly closely related to his PIEV time. Various minimum clearances were established. A driver normally would not position his vehicle with less than five feet of clearance to a leading vehicle, and he would not move into a shoulder-lane gap behind a shoulder-lane vehicle with a time clearance of less than 0.5 seconds. Minimum clearance time for ramp vehicles following a leading ramp vehicle through the system varies with the ramp design and the type of traffic control; the minimum was established at 2.0 seconds with no acceleration lane and yield-sign control, whereas it was set at 1.8 seconds with an acceleration lane and no control. In the latter case sudden, abrupt stops are less likely to occur. No limits were established for the stop-sign condition as the minimum clearance to a leading ramp vehicle never controls. Minimum headway spacings in the moving ramp and shoulder-lane streams were also defined, but these are discussed under traffic and environmental conditions.

Gap Acceptance

Gap acceptance was the final driver characteristic to be modeled. From several studies of this phenomenon conducted in recent years (7, 8, 9, 10, 11, 16, 18, 19, 20), it was possible to develop two families of gap-acceptance models--one for on-ramps without acceleration lanes and one for on-ramps with acceleration lanes. In both cases distinction was made between gap acceptance by stopped first-in-line vehicles and gap acceptance by vehicles that were moving as they passed the first-in-line position.

The gap-acceptance models for on-ramps without acceleration lanes are shown in Figure 8. In the case of stop-sign control on this type of ramp all vehicles were assumed to stop in the first-in-line position before departing from the ramp system. The gap-acceptance model for this condition, derived from data collected by Pearson and Ferreri (16) on the Schuylkill Expressway, was of the mathematical form,

$$Pr(Acpt) = 1 - e^{-\left(\frac{t-t_{min}}{\bar{t}-t_{min}}\right)},$$

where:

$Pr(Acpt)$ = probability of accepting a gap of length, t;

t = any gap greater than t_{min};

t_{min} = minimum acceptable shoulder-lane gap; and

$\bar{t}$ = the average acceptable shoulder-lane gap.

With appropriate parameter substitutions the gap acceptance model for no acceleration and stop-sign control was written as,

$$\Pr(\text{Acpt}) = 1 - e^{-\frac{t - 3.3}{6.5 - 3.3}},$$

or

$$\Pr(\text{Acpt}) = 1 - e^{(1.021 - 0.313t)}.$$

Of course this same model holds for stopped first-in-line vehicles departing from a ramp with no acceleration lane and yield-sign control.

A similar model was proposed by Weiss and Maradudin (18) for vehicles that do not stop in the first-in-line position as would be the case with yield-sign control. This model, written as,

$$\Pr(\text{Acpt}) = 1 - e^{-\frac{t - 2.0}{5.0 - 2.0}}$$

or

$$\Pr(\text{Acpt}) = 1 - e^{(0.67 - 0.33t)},$$

was accepted as a suitable descriptor of gap acceptance at on-ramps with no acceleration lane and yield-sign control.

Gap-acceptance models for on-ramps with acceleration lanes and no sign control are shown in Figure 9. The data used to develop models descriptive of this phenomenon were collected by the Texas Transportation Institute, on contract to the

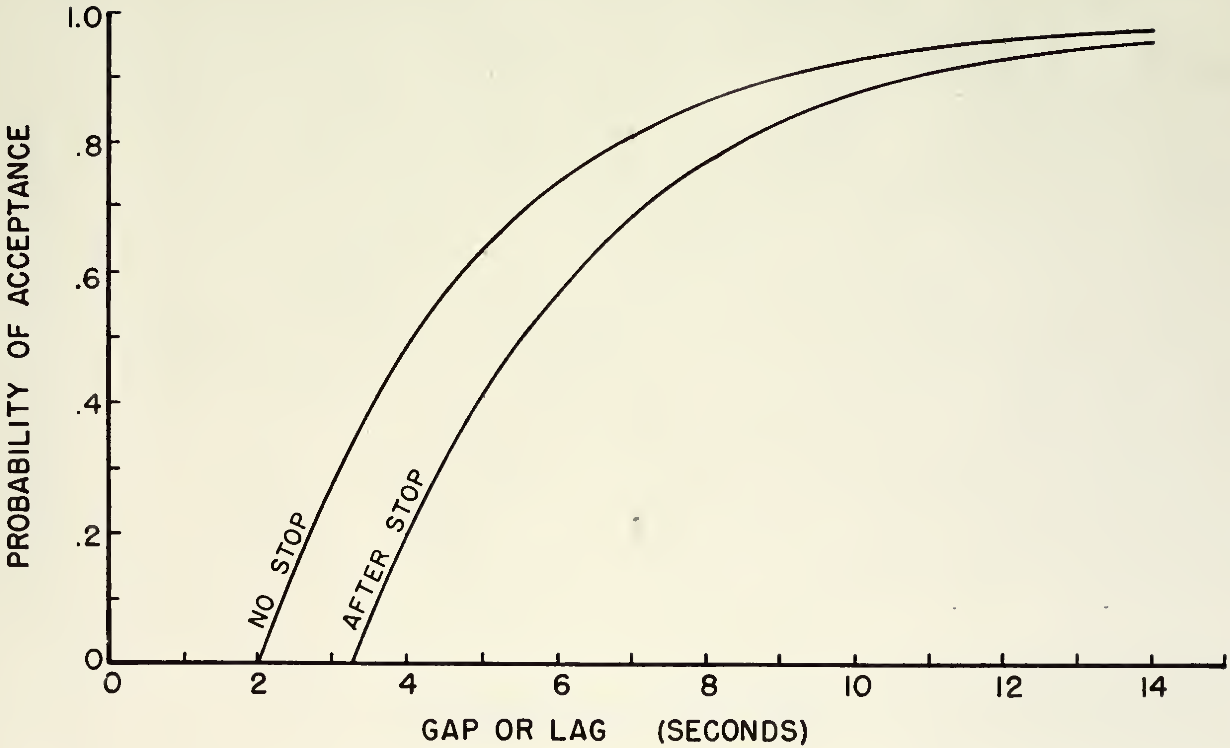

FIG. 8 - CUMULATIVE GAP-ACCEPTANCE DISTRIBUTIONS WITH STOP AND/OR YIELD SIGN CONTROL

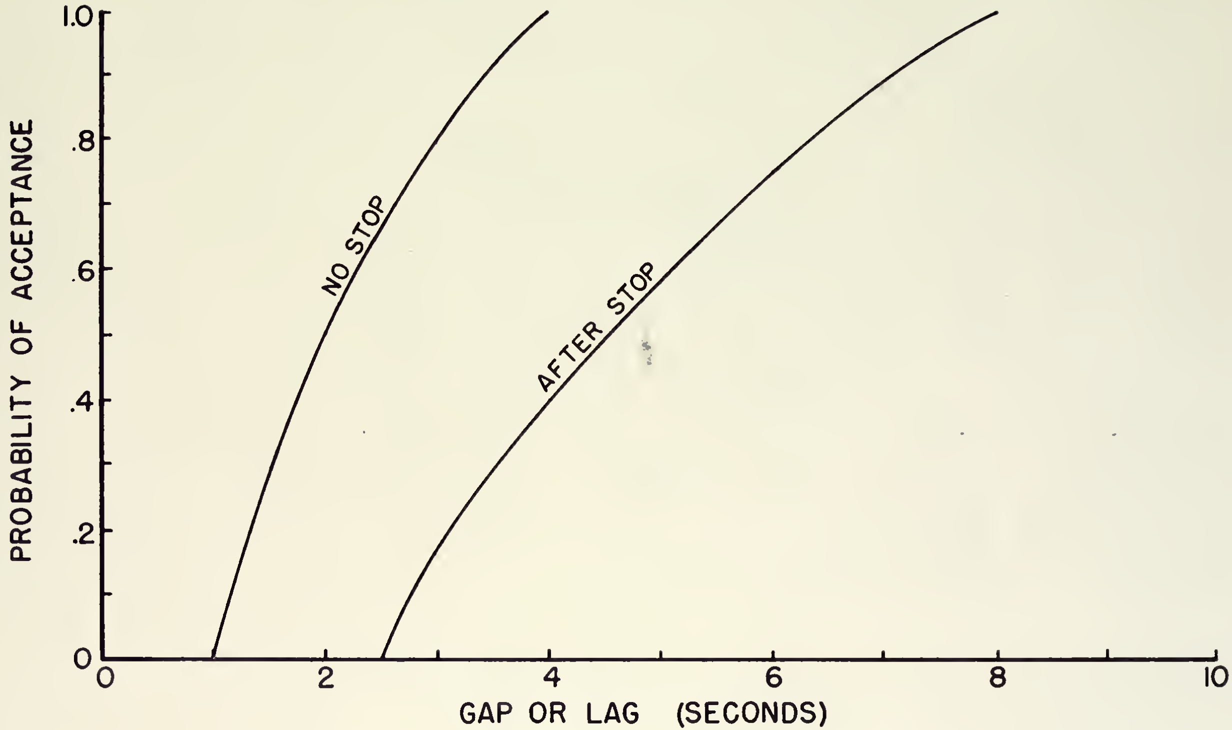

FIG. 9 - CUMULATIVE GAP-ACCEPTANCE DISTRIBUTIONS FOR ACCELERATION LANE WITH NO SIGN CONTROLS

Midwest Research Institute (8). Separate models were defined for vehicles that depart from the system after stopping in the first-in-line position and for vehicles not required to stop in the first-in-line position. Both models follow the mathematical form,

$$Pr(Acpt) = \ln\left(\frac{t}{t_{min}}\right) * \frac{1}{\ln\left(\frac{t_{max}}{t_{min}}\right)},$$

where:

t = any gap length between the limits of t_{min} and t_{max};

t_{min} = minimum acceptable gap; and

t_{max} = minimum gap length for which probability of acceptance is one.

With appropriate parameter substitutions the models for gap acceptance after a stop and with no stop are respectively:

$$Pr(Acpt) = \ln\left(\frac{t}{2.50}\right) * \frac{1}{\ln\left(\frac{8.00}{2.50}\right)}$$

$$= 0.787 + 0.859 \ln(t);$$

and

$$Pr(Acpt) = \ln\left(\frac{t}{1.00}\right) * \frac{1}{\ln\left(\frac{4.00}{1.00}\right)}$$

$$= 0.722 \ln(t).$$

Traffic and Environmental Characteristics

Traffic and environmental characteristics are presented together as they are closely related. Changes in environmental conditions such as weather, lighting, roadside development, etc. tend to modify traffic characteristics. For the purposes of this research environmental conditions were assumed ideal without any statement as to the meaning of "ideal."

Traffic Distribution Between Lanes

Numerous lane-distribution studies have been conducted. Most of these studies (2, 7, 10, 11, 12, 16) reported traffic distribution between lanes as a function of total one-direction freeway volume only. Two recent studies--one published by Moskowitz and Newman (13), and the other published by Hess (4)--reported that lane distribution is dependent upon such variables as number of freeway lanes, total freeway volume, distance upstream to last off-ramp, distance downstream to next off-ramp, traffic volume off at last off-ramp, traffic volume off at next off-ramp and ramp traffic on the ramp under consideration.

After a thorough review of the available data, a decision was made to use Hess's models which were derived from data obtained in a comprehensive, nationwide ramp-capacity study under the sponsorship of the Bureau of Public Roads. The results are presented in two forms for both the four-lane and six-lane freeways. In Figure 10 lane distributions, given as a function of numbers of lanes and of total one-direction volume, can

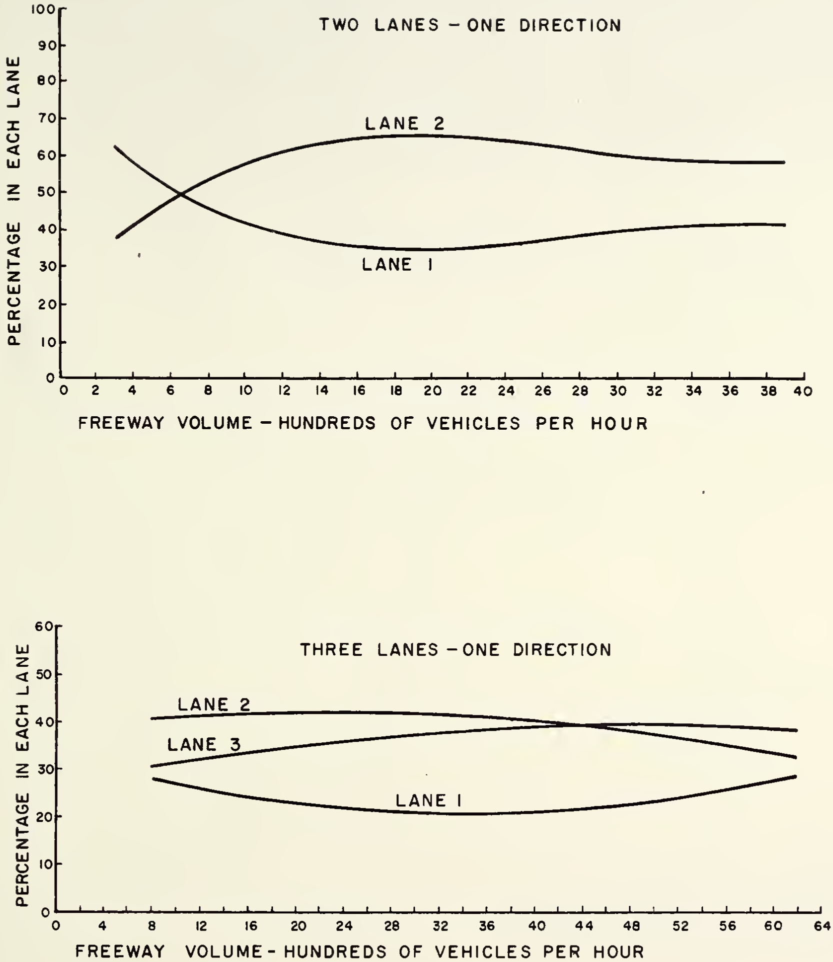

FIG. 10 - DISTRIBUTION OF TRAFFIC VOLUME BETWEEN LANES IN ONE DIRECTION AT APPROACH TO RAMP (FROM J. W. HESS)

be used for approximate estimates of shoulder-lane volume. When more refined estimates are desired the following equations can be used:

1. Four-lane freeways

$$V_s = -1.21 + 0.244V_s - 0.085V_{ur} + 640_{dr}/D_{dr},$$

2. Six-lane freeways

$$V_s = 55 + 0.363V_f - 0.184V_r + 0.022D_{dr} + 0.030V_{dr}$$

where:

V_s = shoulder-lane volume (vph),

V_f = total one-way freeway volume (vph),

V_r = ramp volume (vph),

V_{ur} = volume on adjacent upstream off-ramp (vph),

V_{dr} = volume on adjacent downstream off-ramp (vph), and

D_{dr} = distance to adjacent downstream off-ramp.

The multiple R^2's for these four-lane and six-lane models were 0.92 and 0.80, respectively; the coefficients of variation were reported as 0.086 and 0.134.

Nomographs for the solution of these models are reproduced with Hess's permission in Figures 11 and 12.

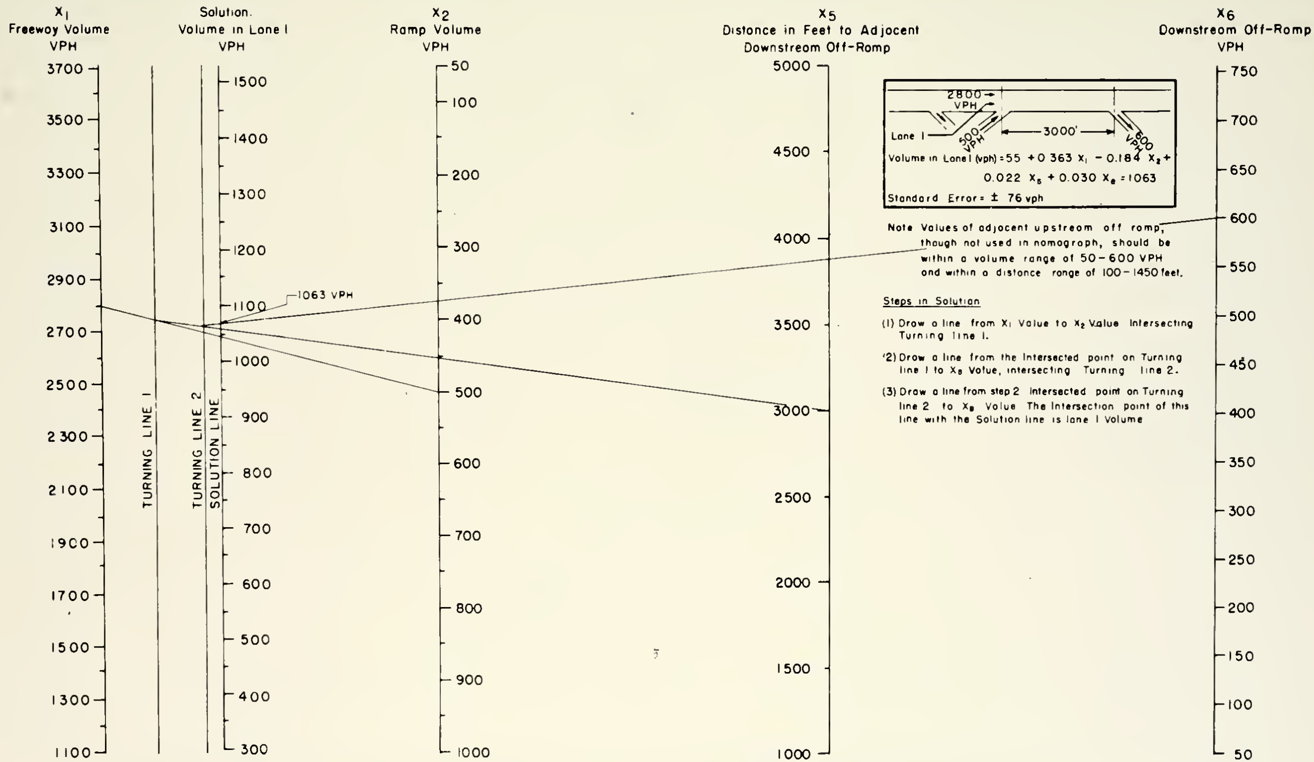

FIG.11 - NOMOGRAPH FOR DETERMINATION OF SHOULDER LANE VOLUME ON FOUR-LANE FREEWAYS
(REPRODUCED BY PERMISSION OF J.W. HESS)

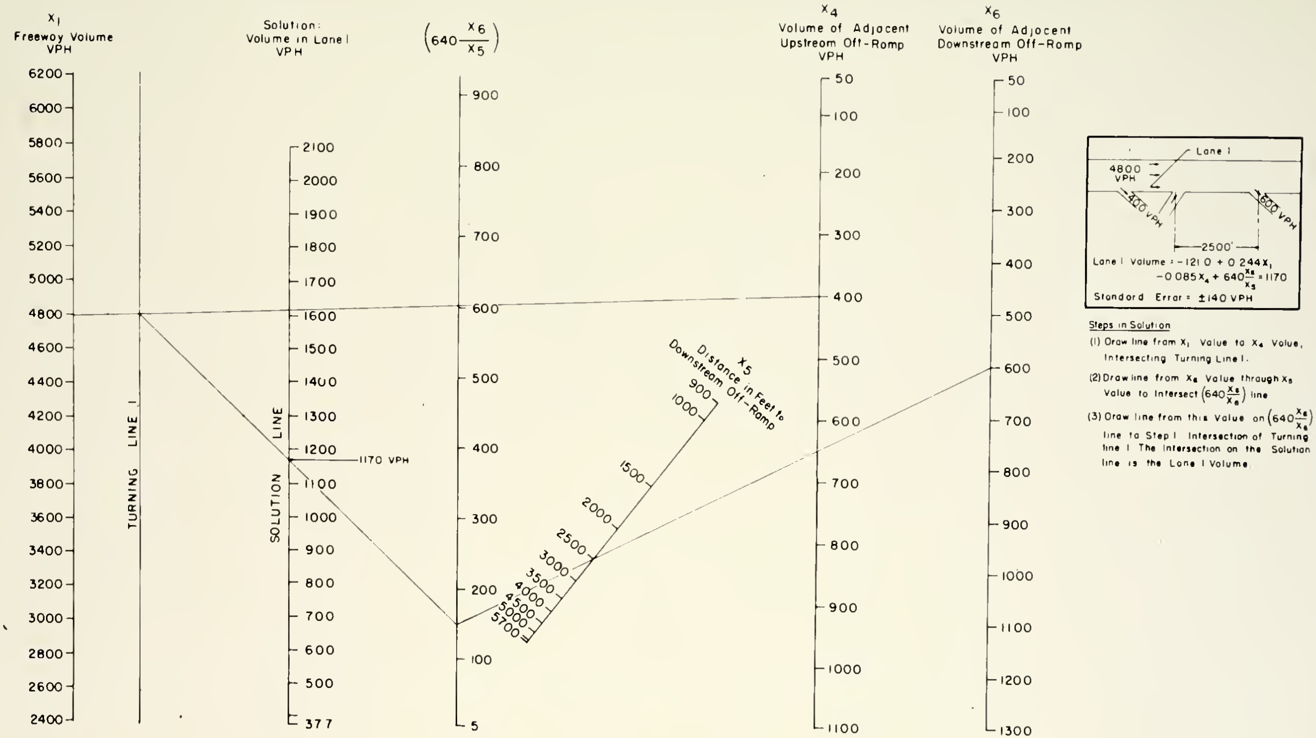

FIG.12 - NOMOGRAPH FOR DETERMINATION OF SHOULDER LANE VOLUME ON SIX-LANE FREEWAYS (REPRODUCED BY PERMISSION OF J.W. HESS)

Headway-Vehicle Generators

Several probabilistic models are available as descriptor's of headways in traffic streams. The more common ones are the negative-exponential distribution (3), the shifted-exponential distribution, the hyper-exponential distribution (6, 17), and a modified binomial distribution (3,20). For the purposes of this study the shifted-exponential model was used to describe headways in the shoulder-lane stream, and the hyper-exponential model was used to describe ramp headways.

The shifted-exponential model is described by the mathematical model,

$$P\ (h \geq t) = e^{-\left(\frac{t-D}{\bar{t}-D}\right)},$$

where:

$P\ (h \geq t)$ = probability that a headway is equal to or greater than t,

t = any time,

$\bar{t}$ = average headway in stream,

= 3600/hourly volume, and

D = minimum allowable headway in the stream.

By trial-and-error process D-values were defined for various shoulder-lane volumes to effect an apparent good fit to the headway curves for multi-lane traffic streams given in the Highway Capacity Manual (2). The varying D-values were

described as a function of the shoulder-lane volume by the expression,

$$D = 0.31 + .0001V_s .$$

A plot of the resulting headway distribution is presented in Figure 13.

The hyper-exponential headway distribution used to describe the ramp traffic stream was originally proposed by Schuhl (17), but the necessary statistical evaluation was performed by Kell (6). This distribution is based on the theory that a traffic stream is made up of two populations of moving vehicles--a restrained population and a free-moving population--each with its own headway distribution. The overall headway distribution is therefore defined by the expression,

$$P(h \geq t) = (1 - \alpha)\, e^{-\left(\frac{t - \Delta_1}{T_1 - \Delta_1}\right)} + e^{-\left(\frac{t - \Delta_2}{T_2 - \Delta_2}\right)} ,$$

where:

α = the proportion of the traffic stream in the restrained population,

$1 - \alpha$ = the proportion of the traffic stream in the free-moving population,

T_1 = average headway of the free-moving population,

T_2 = average headway of the restrained population,

Δ_1 = the minimum allowable headway of the free-moving population, and

Δ_2 = the minimum allowable headway of the restrained population.

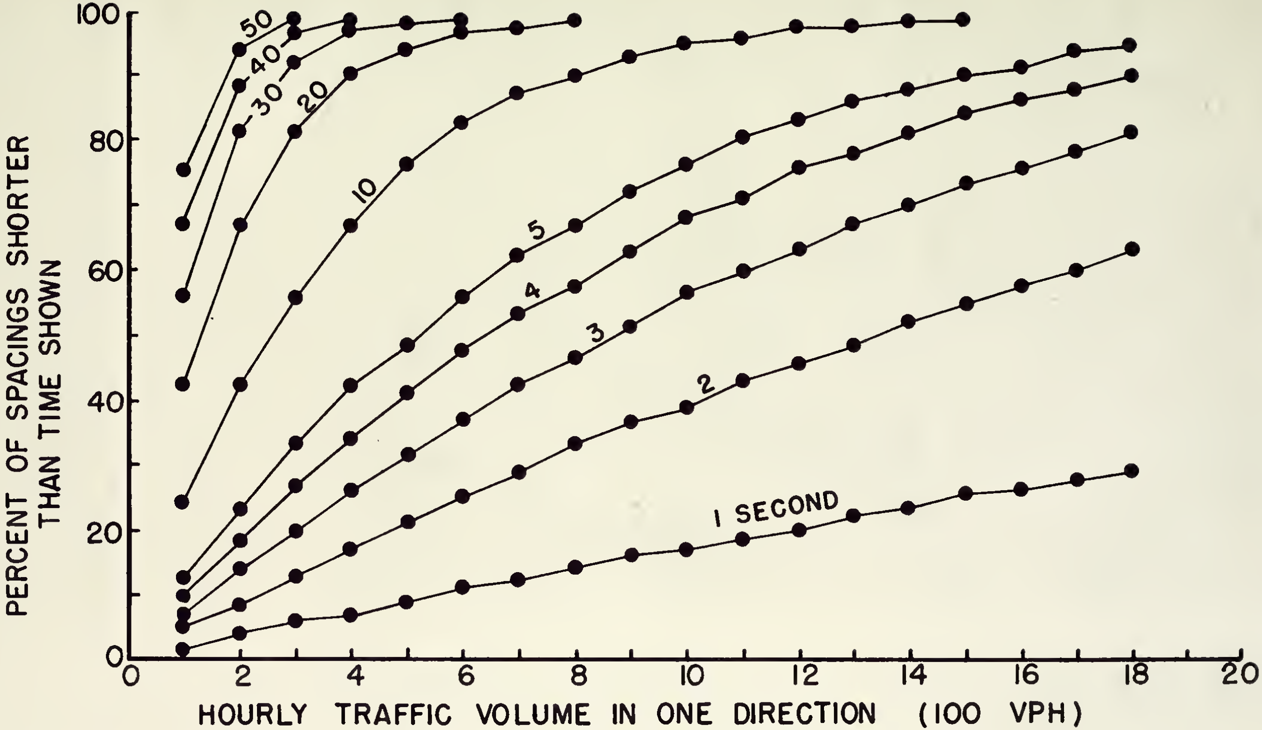

FIG.13 - FREQUENCY DISTRIBUTION OF TIME SPACINGS BETWEEN SUCCESSIVE SHOULDER LANE VEHICLES

Kell evaluated the parameters of this model on a two-lane urban street on which there was negligible passing opportunity. Because the characteristics of a one-lane ramp are not unlike those of the directional channels of an urban street, Kell's model was assumed to afford an adequate description of headways in a ramp stream. The statistical models for estimating the parameters of the headway model are given in the subroutine named RPDATA contained in Appendix B.4; and the resulting headway distributions are shown in Figure 14.

Speed Models

Although speeds are known to follow approximately normal distributions in freeway flow, this variable was described by much simpler models for speed in the ramp and shoulder-lane streams. Ramp entrance speed was assigned a constant value of 30 miles per hour, on the assumption that ramp geometry governs speed regardless of traffic conditions. Shoulder-lane speeds were estimated by an equation approximating two models developed at the Midwest Research Institute (7). The models reported by this group were:

$$SP = 51.062 - 0.0085V_s$$

and

$$SP = 53.703 - 0.0077V_s$$

where:

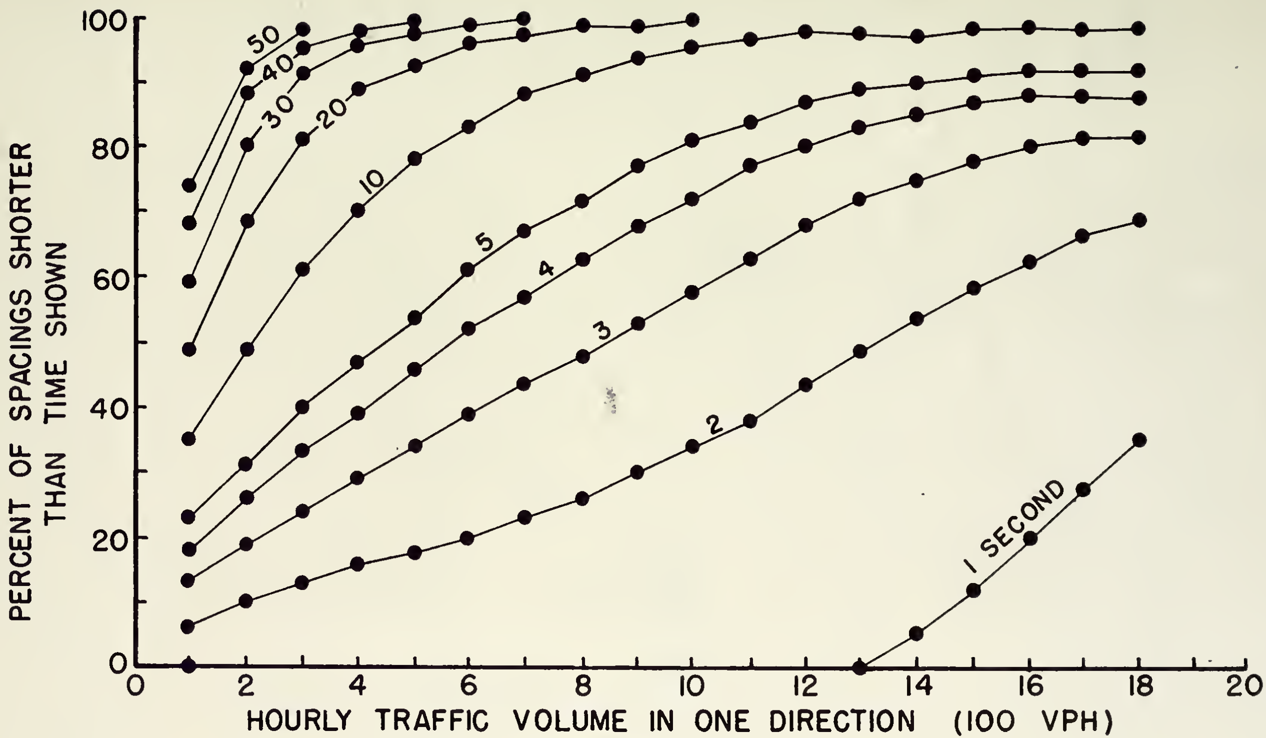

FIG. 14 - FREQUENCY DISTRIBUTION OF TIME SPACINGS BETWEEN SUCCESSIVE RAMP VEHICLES

SP = shoulder-lane speed in the ramp vicinity, and

V_s = shoulder-lane volume (vph).

The values for the coefficients of determination were only 0.337 and 0.545 respectively; whereas the coefficients of variation were 0.18 and 0.16. The model actually used in this study,

$$SP = 52.0 - 0.008V_s ,$$

was an approximate average of those given above.

Rules of Operation

The rules of operation embody a queuing discipline and rules for the driver-vehicle under various traffic conditions.

Queuing Discipline

The definition of an appropriate queuing discipline is relatively simple. The geometry of the ramp area is such that service is provided to ramp traffic on a first-come, first-served basis. That is, no trailing vehicle can preempt service priority and pass a leading vehicle to accept a gap in the shoulder lane.

Vehicle and/or Driver Behavior

A driver arriving at the entry point to the ramp system should immediately decide his course of action. If there is no

acceleration lane and stop-sign control exists, the driver's decision should be to decelerate to a stop. Since there were 108 feet available between the point of entry into the ramp system and the stop-line in this study, this maneuver could be effected at a comfortable rate of deceleration. All drivers were assumed to utilize the same acceleration rates and require the same minimum time and space clearances previously established.

In the cases of no acceleration lane with yield-sign control and an acceleration lane with no sign control, the driver's decision process at the point of entry into the system is somewhat more complex. Upon passing this entry point he should evaluate both shoulder-lane and ramp traffic conditions and establish his course of action. His decision may be to stop upon, or before, reaching the stop-line; or his decision may be to proceed through the ramp area and into the shoulder lane. To arrive at the latter decision the driver has to project the positions and speeds of all other vehicles in the system, as well as his own, to the most critical point in both time and space. His decision to stop or proceed is based entirely upon gap acceptance. He may determine the acceleration-deceleration pattern, within the capabilities established for his vehicle, that will maximize his probability of accepting a gap. It is probable, however, that a driver will not follow the speed pattern that maximizes the gap available to him (maximizing the lag maximizes the probability of accepting the gap), but he undoubtedly considers the best situation that he can create for himself before making a decision.

Some restrictions were necessary, however, to control this complex situation so that a model could be developed; and it was assumed that the driver would not stop on the acceleration lane or at any point on the shoulder-lane side of the stop-line. It was also assumed that in every instance he would stop at the stop-line if an alternate course of action would result in a speed at any point on the shoulder-lane side of the stop-line that would be lower than the speed that would be attained at that point during acceleration from a stop at the stop-line.

MACRO MODELS FOR ON-RAMP CAPACITY

The ramp situation was described in micro detail in the previous chapter. Every important aspect of the ramp traffic system was formulated as a descriptive behavior model or as a rule of operation. This chapter is devoted to the development of a macro framework in which to assemble the micro models as functioning systems. The components were first pulled together into queuing models for analyses of the possible capacities of each of the various design-control combinations--no acceleration lane with stop-sign control, no acceleration lane with yield-sign control, and an acceleration lane with no sign control. Following this, Monte Carlo simulators were constructed for analysis of the practical capacities of these ramp configurations.

Queuing Model for Possible Capacity

By definition possible capacity is the maximum number of vehicles that can be accommodated with a continual backlog or queue of vehicles. Whenever the opportunity occurs for n vehicles to enter the shoulder-lane stream there must be at least n vehicles queued on the ramp to utilize this capacity potential. Although the delay associated with such a traffic

condition may be unreasonable, it was not included in the capacity analysis.

A single general queuing model was written to describe the possible capacity of freeway on-ramps regardless of the design, and regardless of the type of control, if any. This model is as follows:

$$
\begin{aligned}
C_{r_1} = V_s \Big[\, 0 \Big\{ & (F(t_0)) \\
& + (F(t_1) \cdot R(\tau_1)) \\
& + (F(t_2) \cdot R(\tau_2)) \\
& \quad \cdot \\
& \quad \cdot \\
& \quad \cdot \\
& + (F(t_n) \cdot R(\tau_n)) \Big\} \\
+ 1 \Big\{ & (F(t_1) \cdot P(\tau_1)) \\
& + (F(t_2) \cdot P(\tau_2) \cdot R(\tau_1)) \\
& + (F(t_3) \cdot P(\tau_3) \cdot R(\tau_2)) \\
& \quad \cdot \\
& \quad \cdot \\
& \quad \cdot \\
& + (F(t_n) \cdot P(\tau_n) \cdot R(\tau_{n-1})) \Big\}
\end{aligned}
$$

$$+ 2 \left\{ (F(t_2) \cdot P(\tau_2) \cdot P(\tau_1)) \right.$$

$$+ (F(t_3) \cdot P(\tau_3) \cdot P(\tau_2) \cdot R(\tau_1))$$

$$+ (F(t_4) \cdot P(\tau_4) \cdot P(\tau_3) \cdot R(\tau_2))$$

$$\vdots$$

$$\left. + (F(t_n) \cdot P(\tau_n) \cdot P(\tau_{n-1}) \cdot R(\tau_{n-2})) \right\}$$

$$\vdots$$

$$+(n-1) \left\{ (F(t_{n-1}) \cdot P(\tau_{n-1}) \cdot P(\tau_{n-2}) \ . \ . \ . \ P(\tau_2) \cdot P(\tau_1)) \right.$$

$$\left. + (F(t_n) \cdot P(\tau_n) \cdot P(\tau_{n-1}) . \ . \ . P(\tau_3) \cdot P(\tau_2) \cdot R(\tau_1)) \right\}$$

$$+ n \left\{ (F(t_n) \cdot P(\tau_n) \cdot P(\tau_{n-1}) . \ . \ . P(\tau_2) \cdot P(\tau_1)) \right\} \Bigg],$$

where the various terms are defined as:

C_{r_1} = possible capacity of on-ramp (vph);

V_s = shoulder-lane volume (vph);

i = index of potential capacity of a given gap (vehicles);

t_i = upper limit of a gap that can accommodate i vehicles (seconds);

$F(t_0)$ = proportion of total gaps that fall between 0 and t_0;

$F(t_i)_{i=1 \text{ to } n}$ = proportion of total gaps that fall between t_{i-1} and t_i;

τ_i = mean of the gaps that fall between t_{i-1} and t_i

$P(\tau_i)$ = probability of accepting a gap or lag of length, τ_i;

$R(\tau_i)$ = probability of rejecting a gap or lag of length, τ_i; and

n = some very large number approaching ∞ .

Of the several functions that had to be evaluated before a numerical solution could be obtained, only one is common to all three ramp situations under consideration. This single function is $F(t_i)$, the proportion of gaps that fall between t_{i-1} and t_i. It is defined by the shifted-exponential shoulder-lane headway model. For a given volume the probability that a gap will be longer than any t_i is defined as follows:

$$P(h \geq t_i) = e^{-\frac{t_i - D}{\bar{t} - D}},$$

where $P(h \geq t_i)$, $\bar{t}$, and D are as defined in the previous chapter. Of course, this expression can be simplified:

$$P(h \geq t_i) = e^{\delta D} \; e^{-\delta t_i}$$

$$= k \; e^{-\delta t_i},$$

where:

$$\delta = 1/(\bar{t} - D),$$

and

$$k = e^{\delta D}.$$

Since the proportion of gaps that fall into any time range is equal to the difference between the proportion of gaps that are longer than the lower limit and the proportion that are longer than the upper limit,

$$F(t_i) = P(h \geq t_{i-1}) - P(h \geq t_i)$$

or

$$F(t_i) = k\,(e^{-\delta t_{i-1}} - e^{-\delta t_1}) \quad .$$

The remaining functions in the ramp capacity model, $P(\tau_i)$ and $R(\tau_i)$, denote the expected probability with which gaps falling between t_{i-1} and t_i will be accepted and rejected, respectively. Since all of the gaps between any two limits are evaluated in mass, it was necessary to define a representative gap. The mean of the gaps in the range is probably the most appropriate function for this purpose. It is defined by the expression,

$$\tau_i = \frac{t_{i-1}\,e^{-\delta t_{i-1}} - t_i\,e^{-\delta t_1}}{e^{-\delta t_{i-1}} - e^{-\delta t_1}} + \frac{1}{\delta} \quad .$$

Numerical evaluation of $P(\tau_i)$ was obtained by substituting τ_i into the appropriate gap-acceptance equation. $R(\tau_i)$ was set equal to $(1 - P(\tau_i))$. The general assumptions for operation at possible capacity are similar for the three design-control situations. As each opening occurs in the shoulder-lane a stopped queue is assumed to be on the ramp. The first driver in the queue must make his decision to accept or reject the gap using the appropriate gap-acceptance model. (There was one decision model for a stopped first-in-line vehicle on a ramp with an acceleration lane and a second model for stopped first-in-line vehicles on ramps without acceleration lanes.) When the first vehicle of a ramp queue accepts a gap, he must fall in behind the shoulder-lane vehicle with a time clearance of 0.5 seconds. Although this is a very short time spacing the leading shoulder-lane vehicle will be traveling at a higher speed in most instances and will consequently increase the clearance. With yield-sign or no sign control, trailing ramp vehicles enter the shoulder lane at intervals of 2.0 and 1.8 seconds, respectively, provided the remaining lag in the shoulder lane is acceptable to them. This acceptance decision is based upon non-stop gap-acceptance models separately defined for the acceleration-lane and no acceleration-lane situations. Of course, with no acceleration lane and stop-sign control every vehicle is required to come to a stop in the first-in-line position before entering the shoulder lane, and as a consequence these drivers use the same

gap-acceptance decision model regardless of their position at the beginning of the gap. Vehicles accepting successive positions in the same gap enter the shoulder lane at equal intervals of 4.45 seconds.

The limits over which the possible-capacity queuing model was evaluated for each of the design-control conditions were defined by the appropriate gap-acceptance models and by the established minimum clearance times. These limits are presented in Table 1.

The solution of the possible-capacity queuing model for the three design-control conditions was programmed for the IBM 7090 computer using FORTRAN IV coding. Source programs for this analysis are given in Appendix A.

Table 1

TIME LIMITS FOR NUMERICAL SOLUTION OF POSSIBLE-CAPACITY QUEUING MODELS

Index i	t_i--By Design-Control Conditions		
	No Accl-Stop	No Accl-Yield	Accl-No Control
0	3.30	3.30	2.50
1	8.25	5.80	4.80
2	12.70	7.80	6.60
3	17.15	9.80	8.40
.	.	.	.
.	.	.	.
.	.	.	.
.	.	.	.
i	$8.25+(i-1)(4.45)$	$5.80+(i-1)(2.0)$	$4.80+(i-1)(1.8)$

Monte Carlo Simulation of Practical Capacity

The practical capacity of a freeway on-ramp was defined earlier as the maximum volume of vehicles that can enter the through highway during one hour with 85 percent of the drivers being able to leave the ramp without being delayed for more than 60 seconds. Assuming that the flow of ramp traffic into a freeway is governed only by the shoulder-lane traffic stream, it was possible to build a relatively simple simulation model for analysis of the situation.

General Mechanics of the Simulator

The Simulator Time Clock. The flow of ramp traffic onto a freeway via the shoulder lane can be defined as a two-way (or simple) merge with the shoulder-lane stream acting as the master, and the ramp stream functioning as a slave. Although it is somewhat of a simplification of the "real world" the shoulder-lane stream was treated as an independent phenomenon that is in no way altered by the existence of the ramp situation. Shoulder-lane vehicles were generated, using a shifted-exponential headway model, and moved through the ramp area at a constant speed defined by a deterministic speed model. Thus within the ramp area the shoulder-lane traffic stream was made up of abstract objects moving along at a regular speed with random time spacings between them. Concurrently, the ramp vehicles were generated by means of a hyper-exponential headway model. Each of these vehicles was also assigned a constant speed which

was subject to immediate adjustment dependent upon the design of the ramp, the type of control, leading ramp traffic, and of course traffic conditions on the shoulder lane. The generations of these two traffic streams were completely independent of each other; inter-connection was effected by a time clock established as part of the simulator monitor at a point where the shoulder-lane stream and the ramp stream merged in the shoulder lane.

The time clock was also used as a limiting index. Whenever the time required for a simulation run exceeded two times the free-flow time requirement, the simulation run was terminated and traffic flow rates were output. This ramp flow rate is an indication of possible ramp capacity.

Sampling the Simulated Traffic. A simulation run was initiated with an empty system. That is, there were no vehicles in the simulation area when relative simulation time was zero. If the traffic characteristics of the first few simulated vehicles had been recorded and considered in the analysis of the level of performance, they would undoubtedly have biased the results. In order to guard against this bias the simulator was loaded prior to the actuation of the surveillance system. This pre-loading was effected by simulating the flow of 300 ramp vehicles through the ramp area; of course the shoulder-lane flow was simulated simultaneously, but the number of shoulder-lane vehicles involved in the pre-loading operation was a function of the ratio of shoulder-lane volume to ramp volume.

During this initial period no delay or queuing characteristics were recorded. The number of ramp vehicles that were simulated for pre-loading purposes was established arbitrarily; but it was assumed that 300 vehicles (an average of approximately one-half hour of real traffic flow) was adequate to establish equilibrium conditions in the ramp area.

Following the pre-loading operation the surveillance system was actuated and an additional 1000 ramp vehicles were generated and observed. In this case the sample size was established by a dollars constraint rather than by statistical design. After estimates of running times had been prepared from the results of a pilot study, sample sizes were established to conform with the available project funds.

Descriptors of Traffic Performance. The level of performance in the ramp system is defined for every combination of ramp and shoulder-lane volumes and for each design-control situation by 7 variables. Listed under the headings of queuing characteristics and delay characteristics these variables are as follows:

A. Queuing Characteristics

1. percent of vehicles finding a queue on ramp
2. average queue length
3. 85th percentile queue length
4. 90th percentile queue length
5. 95th percentile queue length

B. Delay Characteristics

6. average delay

7. probability that delay exceeds 60 seconds

Although these variables appear obvious, there may be some peculiarities that could lead to confusion. Hopefully any such confusion will be averted by the descriptions of the methods of measurement employed. These measurement techniques are presented in the latter part of this chapter under the heading "Simulator Subroutines."

The Simulator Program

The on-ramp traffic simulator was programmed utilizing both open and closed subroutines under the control of a monitor or master program. The main advantage of this type of structuring is the relative simplicity with which small segments of the overall model can be isolated, programmed, tested, and debugged. In fact, by documenting each of the segmented programs with descriptive comments, written in English, it was possible to prepare a completely intelligible simulator program without first preparing a flow diagram. The advantage of a program that can be readily digested by both the engineer and the computer is obvious.

The Master Program. The master program performed several functions. It served as a library for the storage of definitions that were essential if the program was to be a self-contained

document; it initialized the computer at the start of each simulation run; it served as the simulator monitor during the simulation run; and it prepared a statistical summary and a report describing the simulated situation at the end of each simulation run. With the exception of the monitor function, the work of the master program was of a clerical nature. The portion of the master program that served as the simulator monitor, however, was the "brain" of the simulation system, providing for the complete coordination of the subroutines that described the dynamic traffic situation.

Simulator Subroutines. A series of open and closed subroutines under the control of the monitor effected the simulation of the traffic system. Two subroutines entitled RPDATA and RAMP in combination with five random number generators called RRAND provided the mechanism for the generation of ramp-stream headways; similar subroutines entitled SHDATA, SHLANE, and SRAND provided for the generation of headways in the shoulder lane. The RPDATA and SHDATA subroutines were utilized once at the beginning of each simulation run to calculate values for the parameters of the respective headway distributions. These parameters are functions of the particular volume conditions being simulated.

Random-number generators named RRAND and SRAND were used to generate pseudo-random numbers with which to sample the theoretical ramp and shoulder-lane headway distributions. The

particular random-number generation technique utilized by RRAND and SRAND was formulated at New York University, and programmed in the MAP language for use on the IBM 7090 by Dr. Richard R. Kenyon of Purdue University. A random number, R_i, is generated by the formula,

$$R_i = \epsilon * R_{i-1} \ (\mathrm{Mod} b^n),$$

where:

ϵ = any odd number;

R_0 = a random number of the form $(8*K)+5$ where K is any integer; and

$b^n = 2^{27}$ when programmed in MAP for IBM 7090.

The time required for the generation of a single number is 75 microseconds, and the sequence of numbers does not repeat until 2^{27} numbers have been generated. A nice feature of psuedo-random number generators is the fact that the identical sequences of numbers can be reproduced by merely starting the sequence with the same value for R_0 each time. Of course, when identical sequences of random numbers are used to sample a given theoretical headway distribution, identical sequences of headways result. Unfortunately there was no option available to reset the prepared random number generator between simulation runs. Thus, in order to effect the generation of identical traffic flow combinations it was necessary to prepare five separate RRAND and five separate SRAND subroutines. The simulator has the capability of making five simulation runs

each time it is processed by the computer. At the start of each run a "run designator" was assigned an index between one and five depending upon the number of the run. Each time a random number was required from either the RRAND or SRAND generators a "run designator monitor" checked the run number and called for the next sequential random number from either the RRAND family, designated RRAND1 through RRAND5, or the SRAND family, designated SRAND1 through SRAND5.

The random numbers obtained from RRAND and SRAND were used in a simulated sampling scheme for obtaining random sequences of headways from theoretical ramp and shoulder-lane headway distributions. When it was necessary to generate a shoulder-lane headway the expression describing the distribution of shoulder-lane headways was set equal to the next random number from SRAND. That is, the expression,

$$P(h \geq t) = e^{-\left(\frac{t - D}{\bar{t} - D}\right)} ,$$

was written as

$$e^{-\left(\frac{t - D}{\bar{t} - D}\right)} = R_i \quad .$$

Thus, $t = (D - \bar{t}) * \ln (R_i) + D$,

where D and $\bar{t}$ are as defined in the previous chapter.

Two random numbers were required to sample the hyper-exponential ramp headway distribution. The first number was used to select the portion of the hyper-exponential distribution to be sampled with the second number. The latter step of

the sampling procedure was the same as that described above for the shoulder-lane headways.

Queue surveillance was effected by two un-named, open subroutines--one designed to detect the presence of a queue each time a new ramp vehicle was generated into the system, and the other designed to measure the length of the queue. The subroutines for the stop-sign controlled ramps differed somewhat from those for ramps with yield-sign and no sign control. In the case of stop-sign control a queue was said to exist if upon the arrival of the new ramp vehicle the first-in-line position was still occupied by a leading ramp vehicle. In the case of yield-sign or no sign control a queue was said to exist if the new ramp vehicle could overtake a leading ramp vehicle by proceeding through the system as if it were empty. The length of an existing queue was determined by comparing the arrival times of each new ramp vehicle with the departure times of previous vehicles. Since the characteristics describing each vehicle were stored sequentially it was a simple task to accumulate the number of sequential comparisons required to distinguish those vehicles that had departure times later than the arrival time of the vehicle under observation.

Although no distinction was made between gap and lag acceptance, one of the simulator subroutines was designed to distinguish between a lag and gap as it measured the length of whichever was available. Upon the arrival of each new ramp vehicle a comparison was made between ramp vehicle arrival time and the time of arrival of the last shoulder-lane vehicle.

If the arrival of the last shoulder-lane vehicle was later than ramp arrival time, the ramp vehicle faced an available shoulder-lane lag. The length of this lag was, of course, the difference between the arrival times of the two vehicles. It was conceivable, however, that one or more shoulder-lane vehicles may have passed through the system in the interim period between ramp vehicle arrivals. If this was the case the comparison of ramp vehicle arrival time with the arrival time of the last shoulder-lane vehicle would have yielded a negative difference. With such an outcome additional shoulder-lane vehicles were generated until shoulder-lane arrival time was later than ramp arrival time. The difference between these times was again recorded as the available shoulder-lane lag.

In some cases the ramp driver may have concluded that the available lag was not long enough and refused to use it. He then waited for subsequent breaks or gaps in the shoulder-lane stream. Upon the occurrence of an acceptable gap he departed from the system, and the departure time was recorded.

The ramp driver's decision process for accepting or rejecting available shoulder-lane lags and/or gaps was simulated with three subroutines. Two of these subroutines, designated as ARAND and ACCEPT, are closed subroutines; whereas the third one is an un-named, open subroutine contained within the monitor. The calculated length of the available lag or gap was directed to the ACCEPT subroutine which returned the probability that the gap in question was acceptable to a ramp driver. This probability value was then compared with a random

number generated by ARAND. If the probability value was larger than the random number, the lag or gap was accepted; otherwise it was rejected.

The delay surveillance subroutines were different for each of the three design-control combinations, but in all cases delay was defined as the difference between actual travel time and overall travel time with an empty system. For the purposes of measurement, delay was subdivided into the four following components:

1. time loss during decelerations from entering ramp speed;
2. wait time or time spent waiting in a queue of vehicles in the ramp system as other than the first-in-line vehicle;
3. service time or time spent waiting in the ramp system as the first-in-line vehicle; and
4. time loss during acceleration to shoulder-lane speed.

Time loss during deceleration was the difference between the time required for a vehicle to traverse the deceleration distance while decelerating, and the time for an imaginary vehicle to traverse the same distance while accelerating from ramp speed to shoulder-lane speed. Wait time was measured as the difference between the arrival time of the ramp vehicle under observation and the departure time of the ramp vehicle immediately ahead. Of course this measurement was only pertinent when a ramp vehicle arrived and waited for a queue of

vehicles already on the ramp. In contrast, service time was recorded regardless of the existence or non-existence of a queue. When a new ramp vehicle was generated behind a queue, service time was measured as the difference between the departure time of this new vehicle and the departure time of the previous ramp vehicle. In those instances in which a ramp vehicle was generated on to an empty ramp service time was recorded as the difference between the departure time and the arrival time of the vehicle in question. The final delay-time component, time loss during acceleration, was measured as the difference between the time required to accelerate from departure speed to shoulder-lane speed, and the time required for an imaginary vehicle to traverse the same space with an empty system. In some instances deceleration and acceleration losses became compounded with wait and/or service times. When this occurred, delay was defined by wait time and/or service time without any attempt to separate the deceleration-acceleration losses.

Computer Programs. The practical capacity simulators for the three design-control combinations were programmed to be processed on the IBM 7090 computer using FORTRAN IV and MAP coding (5). The distinctive segments of the simulator programs for the three combinations--no acceleration lane with stop-sign control, no acceleration lane with yield-sign control, and an acceleration lane with no sign control--are presented separately in Appendices B.1, B.2, and B.3. Several

closed subroutines common to the three simulators are presented separately in Appendix B.4 to conserve space. A complete simulator program for any of the three combinations is assembled by appending the common subroutines of Appendix B.4 to the appropriate main program segment selected from Appendix B.1, B.2, or B.3.

RESULTS AND DISCUSSION

The results from the queuing and simulation analyses are presented separately. Solution of the queuing models led directly to the definitions of numerical, possible capacity limits for the three freeway on-ramp design-control conditions--no acceleration lane with stop-sign control, no acceleration lane with yield-sign control, and an acceleration lane with no sign control. These numerical definitions are presented in graphical form. An accompanying table summarizes the associated queuing conditions. In contrast, the results obtained from the simulation did not directly define practical capacities. Each simulation run produced a record describing delay and queue characteristics at various combinations of shoulder-lane and ramp volumes. Subsequent statistical analyses of the delay characteristics provided the basis for the definitions of practical capacity. Related queuing characteristics are described by both graphical and mathematical models.

Results of the Queuing Analysis

Numerical Limits for Possible Capacity

The possible capacities of freeway on-ramps obtained from solutions of the queuing model are shown in Figure 15 for the

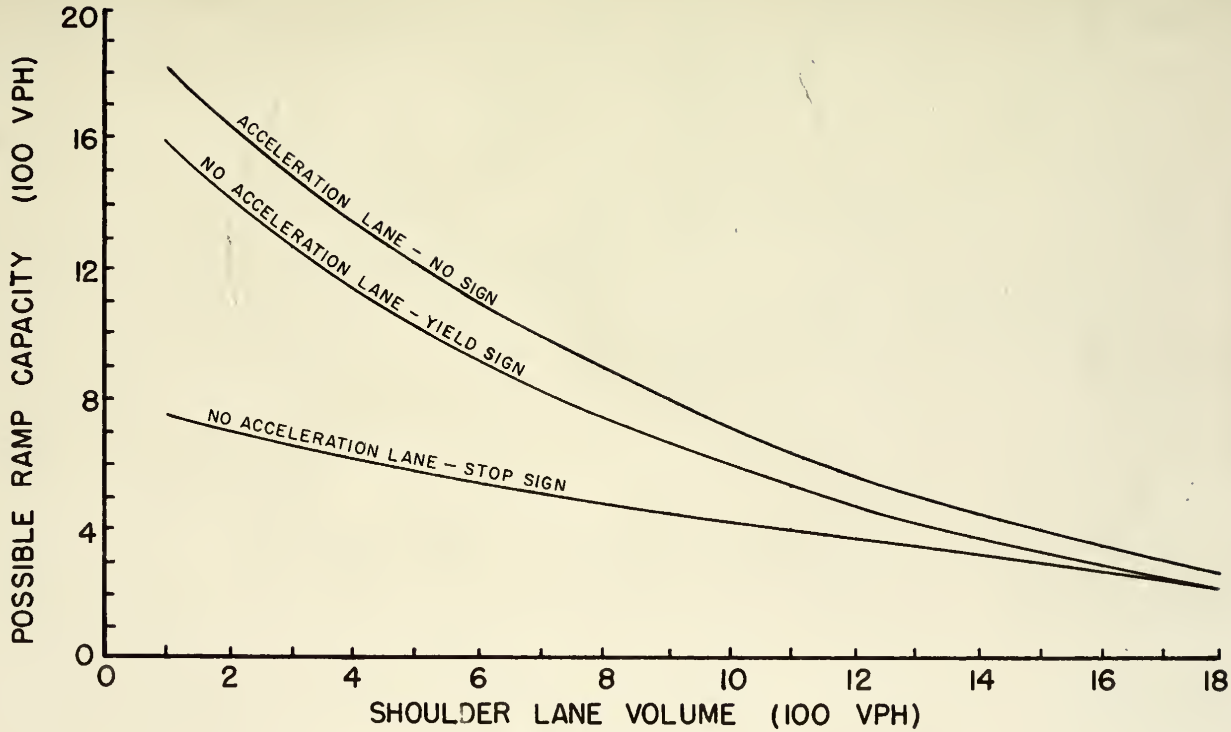

FIG. 15 - POSSIBLE CAPACITIES OF FREEWAY ON-RAMPS

three design-control combinations. Although there was practically no scatter in the possible capacity plots, statistical analyses were made for the purpose of developing empirical prediction models. Nearly perfect least-square fits were obtained using an equation of the form,

$$y = e^{(a + bx + cx^2)} .$$

The results of these statistical analyses are summarized in Table 2 for the three design-control combinations. As expected the on-ramp with an acceleration lane and no sign control had the highest possible capacity; the lowest capacity was realized on the on-ramp with no acceleration lane and stop-sign control. The capacity of the ramp with no acceleration lane and yield-sign control approaches that of the ramp with an acceleration lane and no sign control at low shoulder-lane volumes. This is readily explained. At shoulder-lane volumes approaching zero flow the ramp stream can move almost continuously with minimum time spacings between successive vehicles. Since there is only a small difference in the minimum allowable spacings for the two conditions under consideration the potential capacities approach each other, although they cannot be equal. With no acceleration lane and yield-sign control the 2.0 seconds minimum spacing permits a maximum capacity potential of 1800 vehicles per hour; a maximum capacity potential of 2000 vehicles per hour is possible with the 1.8 second minimum time spacing imposed on ramp vehicles with an acceleration lane available.

TABLE 2

SUMMARY OF LEAST-SQUARE EQUATIONS FOR PREDICTING POSSIBLE CAPACITIES OF FREEWAY ON-RAMPS

Prediction Model: $y = e^{(a+bx+cx^2)}$*

Regression Coefficients			Statistical Characteristics			
			Limits of Analysis-x			
a	b	c	Low	High	R^2	Number of Observations
No Acceleration Lane and Stop-Sign Control						
+6.6478	-0.0004829	-0.0000001038	100	1800	.999	18
No Acceleration Lane and Yield-Sign Control						
+7.4567	-0.0009773	-0.0000000813	100	1800	.999	18
Acceleration Lane and No Sign Control						
+7.5888	-0.0008983	-0.0000001099	100	1800	.999	18

* y = Possible Capacity -- vph
x = Shoulder-Lane Volume -- vph

Little or no capacity difference results from differences in the gap-acceptance models for the two situations. At volumes approaching zero in the shoulder lane almost all gaps are long enough to be completely acceptable to all ramp drivers.

As shoulder-lane volumes increase from zero, however, the length of available gaps decreases with the consequence that more of the vehicles on the ramp with yield-sign control are forced to stop than on the ramp with an acceleration lane. Since gap acceptance differences become even more critical after a stop, the possible capacities of the two ramp situations become widely divergent.

At high shoulder-lane volumes the possible capacity of the yield-sign controlled ramp approaches that of the stop-sign controlled ramp. This can be attributed to the similarity between stop- and yield-sign control that occurs as traffic conditions on the shoulder lane become congested. With stop-sign control, a stop is mandatory before entering the shoulder lane; with yield-sign control there is no absolute stop requirement, but due to the shortage of acceptable gaps in the shoulder lane most ramp vehicles find it necessary to stop before merging with the shoulder-lane stream. Of course all vehicles stopped in the first-in-line position on a ramp without an acceleration lane must utilize the same decision model for gap acceptance regardless of the type of control.

Queuing Conditions at Possible Capacity

By definition possible capacity can only be achieved when there is a continual backlog or queue of ramp vehicles of sufficient length to fill every single shoulder-lane gap that moves past the ramp terminal. Implications of the queuing conditions that are necessary in order to realize the possible capacities of the various on-ramp designs are presented in Tables 3, 4, and 5. Briefly, these tabulations summarize the extent to which excess shoulder-lane capacity must be utilized by various length queues if the ramp is to flow at possible capacity. Since the arrival of shoulder-lane gaps at the ramp terminal is random, it is necessary to continually have enough vehicles stored on the ramp to fill the longest expected shoulder-lane gap.

For example, with a shoulder-lane volume of 800 vehicles per hour flowing past an on-ramp with no acceleration lane and yield-sign control, it is possible that a shoulder-lane gap might occur that is long enough to accommodate 20 ramp vehicles. It is therefore necessary that a 20-car queue be continually available on the ramp if 100 percent of the possible ramp capacity is to be utilized.

As another example, the possible capacity of a ramp with an acceleration lane and no sign control is 1816 vehicles per hour when the shoulder-lane is carrying 100 vehicles per hour. Approximately 72 percent of this capacity is dependent upon utilization by queues with lengths greater than 20 vehicles.

TABLE 3

POSSIBLE CAPACITY OF FREEWAY ON-RAMP

No Acceleration Lane -- Stop-Sign Control

Shoulder Lane Volume	Amount of Capacity Utilized by Queues of Length Equal to or Shorter than X												Possible Ramp Capacity
	Length of Queue -- X Vehicles												
(VPH)	1	2	3	4	5	6	7	8	9	10	15	20	(VPH)
100	12	30	54	83	114	147	181	216	250	283	433	544	751
200	40	94	157	221	284	343	396	443	485	521	632	677	701
300	76	166	257	339	410	468	514	550	577	598	645	655	658
400	115	232	336	418	480	525	556	577	591	601	616	618	618
500	152	286	390	462	509	539	557	567	574	577	582	582	582
600	186	327	422	479	512	529	539	544	546	547	549	549	549
700	215	354	436	478	499	509	514	516	517	517	517	517	517
800	238	370	436	466	479	484	486	487	487	487	487	487	487
900	256	375	427	447	455	457	458	458	458	458	458	458	458
1000	268	373	412	425	429	430	430	430	430	430	430	430	430
1100	274	364	392	400	402	403	403	403	403	403	403	403	403
1200	275	351	370	375	376	376	376	376	376	376	376	376	376
1300	272	333	347	350	350	350	350	350	350	350	350	350	350
1400	265	314	323	324	324	324	324	324	324	324	324	324	324
1500	255	292	298	299	299	299	299	299	299	299	299	299	299
1600	242	270	274	274	274	274	274	274	274	274	274	274	274
1700	226	247	249	249	250	250	250	250	250	250	250	250	250
1800	209	224	225	226	226	226	226	226	226	226	226	226	226

TABLE 4

POSSIBLE CAPACITY OF FREEWAY ON-RAMP

No Acceleration Lane -- Yield-Sign Control

Shoulder Lane Volume	Amount of Capacity Utilized by Queues of Length Equal to or Shorter than X												Possible Ramp Capacity
	Length of Queue -- X Vehicles												
(VPH)	1	2	3	4	5	6	7	8	9	10	15	20	(VPH)
100	5	15	28	44	63	85	109	134	162	190	347	511	1598
200	18	50	90	137	189	244	302	361	420	479	749	963	1426
300	36	93	162	238	318	398	477	552	624	691	952	1107	1277
400	55	137	231	329	425	515	599	676	743	803	1001	1089	1146
500	75	179	291	400	501	591	669	736	792	838	969	1012	1029
600	94	215	337	449	547	628	695	748	790	823	902	920	926
700	111	244	370	478	566	635	688	728	757	779	823	831	832
800	125	266	390	489	565	621	660	689	708	721	745	748	748
900	138	280	397	485	548	591	620	639	651	658	670	671	671
1000	147	288	395	471	520	552	572	584	592	596	602	602	602
1100	154	289	385	448	486	509	522	529	533	536	538	539	539
1200	158	285	369	419	447	463	472	476	478	480	481	481	481
1300	160	276	347	387	407	418	423	426	427	427	428	428	428
1400	159	264	323	353	367	374	377	379	379	379	380	380	380
1500	155	248	296	318	328	333	334	335	335	335	336	336	336
1600	150	231	269	285	291	294	295	295	295	295	295	295	295
1700	143	212	241	252	256	258	258	259	259	259	259	259	259
1800	134	192	214	222	224	225	225	225	225	225	225	225	225

TABLE 5

POSSIBLE CAPACITY OF FREEWAY ON-RAMP

Acceleration Lane -- No Sign Control

Shoulder Lane Volume	Amount of Capacity Utilized by Queues of Length Equal to or Shorter than X												Possible Ramp Capacity
	Length of Queue -- X Vehicles												
(VPH)	1	2	3	4	5	6	7	8	9	10	15	20	(VPH)
100	5	14	25	40	58	79	101	126	153	180	336	503	1816
200	17	46	83	129	180	236	294	355	416	478	772	1017	1648
300	34	89	154	231	313	397	482	564	644	720	1030	1230	1493
400	54	134	226	327	430	531	626	714	795	868	1125	1251	1351
500	74	178	291	408	521	625	719	801	872	932	1117	1186	1222
600	94	218	344	469	582	680	764	834	890	936	1057	1091	1103
700	113	252	385	509	615	702	772	827	869	902	975	991	994
800	129	278	412	529	624	698	753	794	824	845	887	894	895
900	143	298	427	534	615	674	716	745	765	778	801	804	804
1000	154	309	430	524	591	637	668	687	700	708	720	721	721
1100	163	314	425	505	558	592	614	627	634	639	645	645	645
1200	168	313	411	478	519	544	558	566	571	573	576	576	576
1300	171	307	392	445	476	494	503	508	510	512	513	513	513
1400	171	296	368	410	432	444	450	453	454	455	455	455	455
1500	168	281	341	373	389	396	400	402	402	403	403	403	403
1600	164	263	312	336	347	352	354	354	355	355	355	355	355
1700	157	244	282	299	307	310	311	311	311	311	312	312	312
1800	149	223	252	265	269	271	272	272	272	272	272	272	272

This means that there must be a queue with some length in excess of 20 vehicles (the actual length is not defined) present on the ramp at all times.

At the other end of the scale, the possible capacity of a ramp with no acceleration lane and stop-sign control is 226 vehicles per hour when the shoulder lane is carrying 1800 vehicles per hour. If at least a one-vehicle queue is continually present, 93 percent of the total possible capacity can be utilized. It would require the continual presence of a four-vehicle queue to utilize 100 percent of the potential possible capacity.

Simulation Results

Generated Versus Requested Volumes

The ramp and shoulder-lane traffic flows were generated by a simulated-sampling technique whereby theoretical headway distributions were sampled using random numbers. At the start of each simulation run parameters of the headway distributions were established for the particular volumes desired. The generated volumes varied from the requested volumes due partly to sampling error, and partly to small errors inherent in the equations for predicting the volume related distribution parameters.

The requested and generated ramp volumes are compared in Table 6. In ten of the twelve volume conditions considered the simulated ramp volumes were slightly lower than the requested volumes. Since each simulation run was continued until 1300 ramp

TABLE 6

COMPARISON OF RAMP VOLUMES GENERATED BY SIMULATOR WITH RAMP VOLUMES REQUESTED

Ramp Volumes -- (VPH)	
Requested	Generated
100	92
200	194
300	297
400	405
500	503
600	598
700	694
800	783
900	872
1000	957
1100	1052
1200	1156

vehicles had been generated, and since the same sequence of random numbers was utilized for each run, identical ramp volumes were generated each time the same volume was requested. In contrast the number of shoulder-lane vehicles generated at a given volume level was dependent upon the ramp volume being generated with the result that the simulated shoulder-lane volumes were different for almost every run. A comparison between the requested and the generated shoulder-lane volume is given in Table 7. Again it should be noted that the majority of the generated volumes are slightly lower than the requested volumes.

TABLE 7

SHOULDER-LANE VOLUMES GENERATED BY SIMULATOR AT
VARIOUS REQUESTED COMBINATIONS OF RAMP AND SHOULDER-LANE TRAFFIC VOLUMES

Shoulder-Lane Volume Requested -- (VPH)	Ramp Volume Requested -- (VPH)											
	100	200	300	400	500	600	700	800	900	1000	1100	1200
100	100	97	93	91	89	89	90	91	85	82	80	77
200	197	200	194	194	185	186	182	180	180	178	180	178
300	300	297	302	294	291	291	282	280	277	277	271	267
400	395	396	394	402	393	387	391	390	381	373	373	371
500	498	494	494	497	503	493	493	482	489	487	481	471
600	598	598	595	594	598	603	587	590	584	576	587	585
700	694	701	694	693	694	693	704	690	687	689	677	672
800	792	792	791	791	788	789	799	804	795	790	784	788
900	891	890	897	887	893	893	891	900	900	903	895	
1000	992	993	1003	990	991	989	994	990	993	994		
1100	1097	1098	1099	1089	1086	1095	1084	1092	1089			
1200	1199	1198	1190	1200	1188	1191	1192	1193				
1300	1298	1296	1287	1300	1282	1283						
1400	1393	1390	1386	1402	1396							
1500	1495	1490	1494	1498	1502							
1600	1596	1587	1593	1585								
1700	1695	1685	1698									
1800	1796	1783										

Traffic Performance By Type of On-Ramp

Traffic performance for each of the three different ramp designs was described for every combination of ramp and shoulder-lane volumes by seven variables--the percent of the ramp vehicles that arrive to find a queue on the ramp, the average length of queue found on the ramp, the 85th, 90th, and 95th percentile queue lengths found on the ramp, the average delay incurred by a ramp vehicle, and the probability that the delay incurred by a ramp vehicle exceeds 60 seconds. Statistical analyses were performed on the data describing the percent finding a queue, the average queue length, the average delay, and the probability that delay exceeds 60 seconds; and least-square prediction models were constructed to explain the variation in each of these characteristics as a function of shoulder-lane volume, with ramp volume held constant at each of several different levels.

No Acceleration Lane--Stop-Sign Control. Analyses of the stop-sign controlled ramp situation were conducted for shoulder-lane volumes ranging from 100 to 1800 vehicles per hour. The range of ramp volumes studied at each shoulder-lane volume varied from 100 vehicles per hour to the possible capacity of the ramp defined for the given shoulder-lane volume. Since the maximum ramp capacity that can be realized even at very low shoulder-lane volumes is only slightly in excess of 700 vehicles per hour no simulation runs were considered above this limit.

The results describing the percent of vehicles finding a queue, average queue length, average delay, and the probability that delay exceeds 60 seconds are plotted in Figures 16, 17, 18, and 19, respectively. In each case the plots represent empirical equations fitted to observed data by the "method of least-squares." A separate analysis was made to determine the relationship between a given characteristic (average queue, average delay, etc.) and shoulder-lane volume at each level of ramp volume.

The results of the statistical analysis of each family of curves, and the data included in each analysis, are summarized in the two consecutive tables following each figure. These tables are numbered 7 through 14.

The equations fitted to each of the four characteristics were all of the same general form,

$$y = e^{(a + bx + cx^2)},$$

where:

y = the ramp characteristic under consideration, and

x = shoulder-lane volume expressed in vehicles per hour.

The regression coefficients, multiple R^2's, ranges of analyses, and the number of observations included in each analysis are presented in Tables 8, 10, 12, and 14. The apparent amounts of variability (R^2) explained by each of the derived equations are very high. In 18 out of 28 fits the R^2's had values in excess of 0.980, and in 24 of the 28 fits they exceeded 0.950.

In no case was an R^2 of less than 0.936 obtained. Care should be exercised, however, in interpreting the significance of these values. They are not true estimates of the proportion of the variability in the y's that is explained by the model; rather, they are estimates of the proportion of the variability in the natural logarithms of the y's that are explained by the following transformed model,

$$\ln(y) = a + bx + cx^2 .$$

The observed data sets were too numerous to be plotted with the empirical fits. Consequently, they are summarized in Tables 9, 11, 13, and 15. It is apparent that the summaries in these tables are not complete; data are given for only even 100 vehicle per hour increments of ramp and shoulder-lane volumes. In some cases, however, it was necessary to run the simulator at intermediate volume conditions to obtain an adequate number of data sets for the statistical analysis, but for convenience of presentation these intermediate points have been left out of the summaries.

No Acceleration Lane--Yield-Sign Control. No ramp volumes were studied in excess of 1200 vehicles per hour although the maximum possible capacity of a ramp with yield-sign control is nearly 1600 vehicles per hour under low shoulder-lane volume conditions. Analysis was restricted to this lower limit due to the characteristics of the ramp-vehicle generator. The

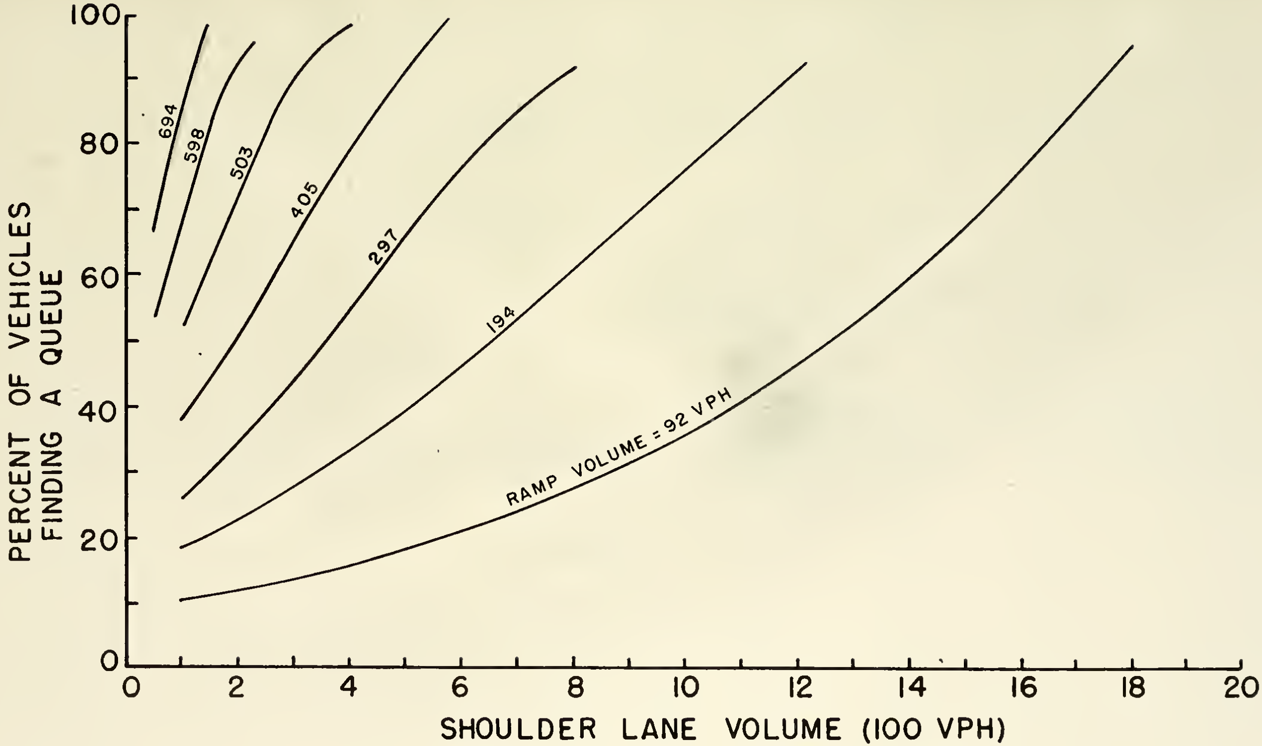

FIG. 16 - PERCENTAGE OF VEHICLES FINDING A QUEUE WITH STOP SIGN CONTROL

TABLE 8

EQUATIONS FOR PREDICTION OF PERCENT OF VEHICLES FINDING QUEUE

No Acceleration Lane -- Stop-Sign Control

Prediction Model: $y = 100 \cdot e^{(a+bx+cx^2)}$ where x is shoulder-lane volume expressed in vehicles per hour.

Ramp Volume (VPH)	Regression Coefficients			Statistical Characteristics			
				Range of Analysis			
	a	b	c	Low x	High x	R^2	Number of Observations
100	-2.4047	+.0014981	-.0000001014	100	1800	.997	18
200	-1.8843	+.0022404	-.0000006166	100	1200	.990	12
300	-1.6537	+.0033658	-.0000017414	100	800	.986	8
400	-1.3084	+.0036523	-.0000024264	100	600	.988	6
500	-1.0974	+.0050784	-.0000058851	100	400	.996	7
600	-0.9604	+.0073962	-.0000147089	50	225	.998	8
700	-0.8215	+.0096902	-.0000286037	50	150	.989	5

TABLE 9

PERCENT OF VEHICLES FINDING QUEUE

No Acceleration Lane -- Stop-Sign Control

	Ramp Volume -- (100 VPH)						
Shoulder-Lane Volume--(100 VPH)	1	2	3	4	5	6	7
1	10.0	17.6	24.5	37.8	52.3	70.2	88.4
2	12.1	25.1	38.5	53.0	74.8	92.5	
3	14.8	27.8	44.8	60.8	90.9		
4	15.5	32.8	55.9	80.0	99.8		
5	18.7	43.3	65.2	95.3			
6	22.2	49.4	75.9	98.8			
7	26.1	50.8	81.1				
8	28.9	58.7	97.2				
9	31.0	68.0	100.0				
10	36.1	74.4					
11	41.0	87.1					
12	44.6	94.4					
13	54.7	100.0					
14	55.6						
15	69.8						
16	77.8						
17	87.1						
18	97.8						

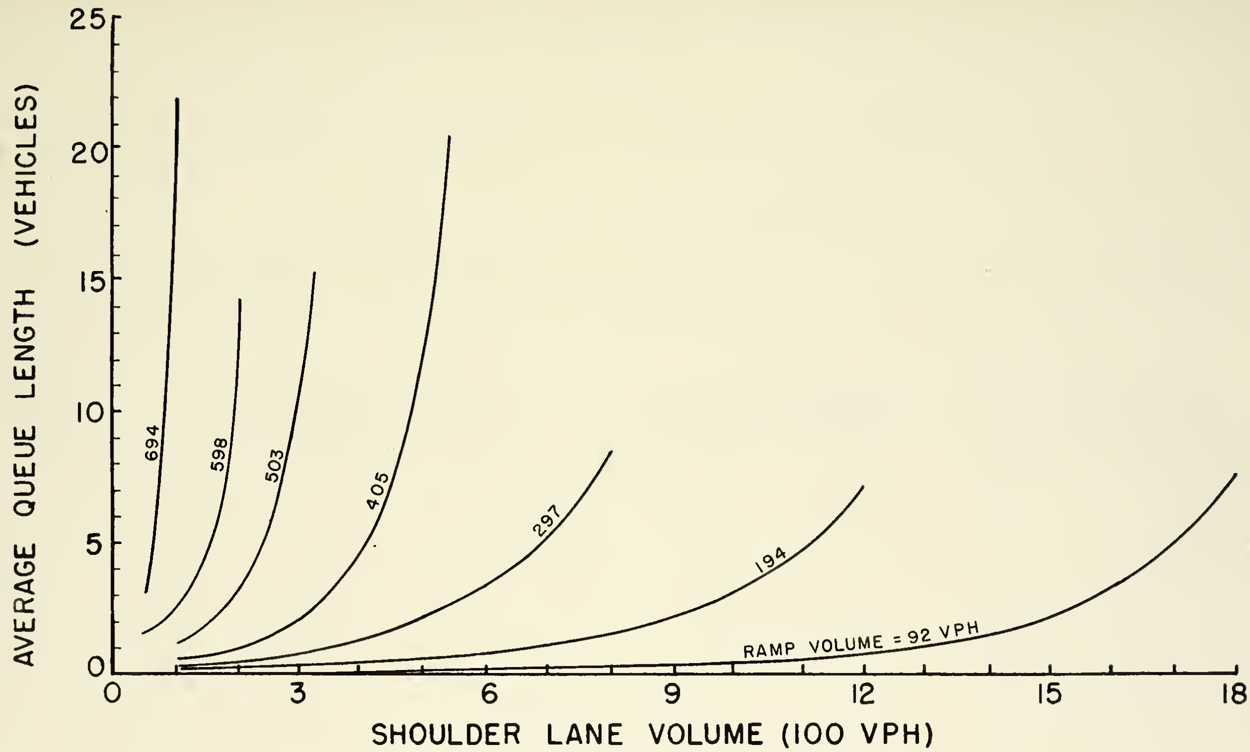

FIG. 17 - AVERAGE QUEUE LENGTH ON RAMP WITH STOP SIGN CONTROL

TABLE 10

EQUATIONS FOR PREDICTION OF AVERAGE QUEUE LENGTHS

No Acceleration Lane -- Stop-Sign Control

Prediction Model: $y = e^{(a+bx+cx^2)}$ where x is shoulder-lane volume expressed in vehicles per hour.

Ramp Volume (VPH)	Regression Coefficients			Statistical Characteristics			
				Range of Analysis			Number of
	a	b	c	Low x	High x	R^2	Observations
100	-1.9975	+.0000625	+.0000012797	100	1800	.963	18
200	-1.6397	+.0018591	+.0000009418	100	1200	.971	12
300	-1.5500	+.0043815	+.0000002995	100	800	.984	8
400	-0.9395	+.0032663	+.0000071594	100	600	.996	6
500	-0.7899	+.0082321	+.0000079973	100	400	.999	7
600	+0.3085	-.0010991	+.0000643069	50	225	.998	8
700	-2.0566	+.0751588	-.0002365566	50	150	.972	5

TABLE 11

AVERAGE QUEUE LENGTHS -- (VEHICLES)

No Acceleration Lane -- Stop-Sign Control

		Ramp Volume -- (100 VPH)						
		1	2	3	4	5	6	7
Shoulder-Lane Volume--(100 VPH)	1	0.11	0.20	0.28	0.55	1.17	2.21	21.10
	2	0.13	0.34	0.61	1.16	3.22	13.42	
	3	0.16	0.35	0.86	1.82	11.49		
	4	0.17	0.42	1.42	4.25	42.24		
	5	0.22	0.84	1.96	12.97			
	6	0.27	0.91	2.92	35.82			
	7	0.33	1.24	4.38				
	8	0.39	1.59	10.28				
	9	0.43	1.67	66.05				
	10	0.56	2.49					
	11	0.65	4.40					
	12	0.84	9.34					
	13	1.16	61.43					
	14	1.21						
	15	2.38						
	16	3.04						
	17	4.42						
	18	21.21						

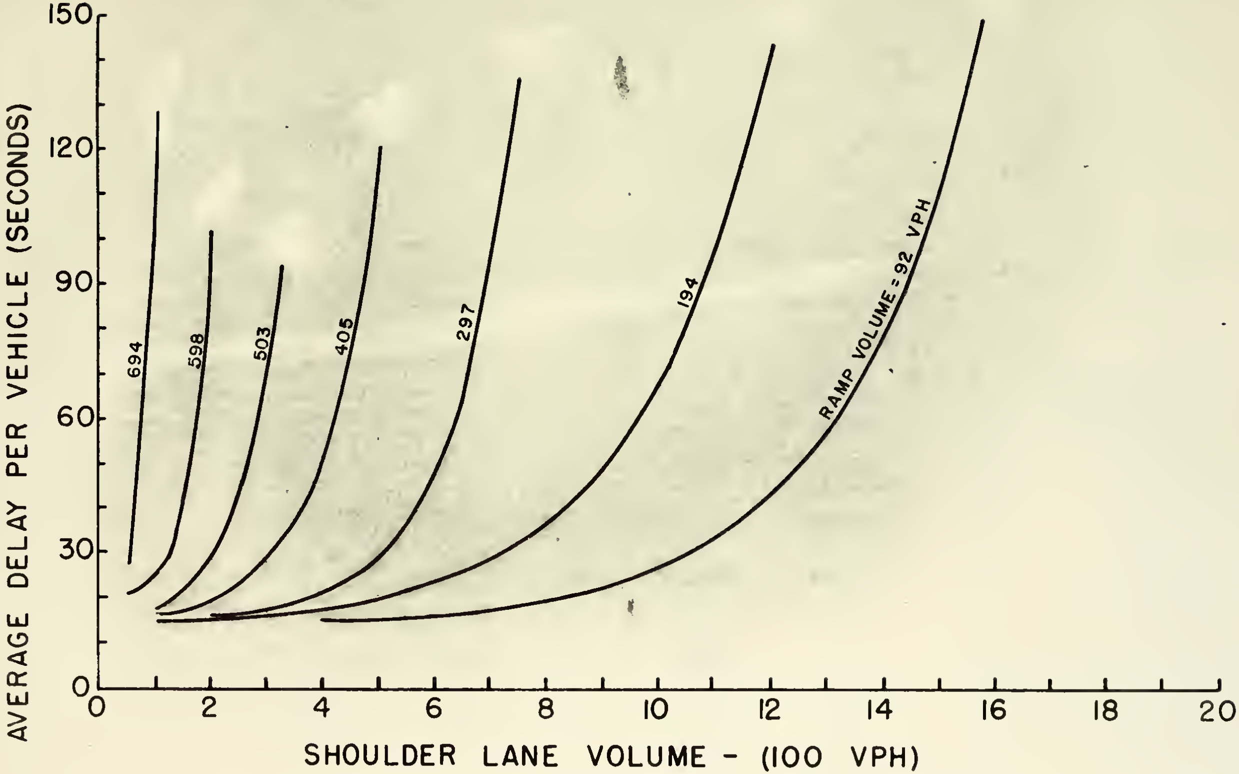

FIG. 18 - AVERAGE DELAY TO RAMP VEHICLES WITH STOP SIGN CONTROL

TABLE 12

EQUATIONS FOR PREDICTION OF AVERAGE DELAY -- (SECONDS)

No Acceleration Lane -- Stop-Sign Control

Prediction Model: $y = e^{(a+bx+cx^2)}$ where x is shoulder-lane volume expressed in vehicles per hour.

Ramp Volume (VPH)	Regression Coefficients			Statistical Characteristics: Range of Analysis			
	a	b	c	Low x	High x	R^2	Number of Observations
100	+2.9952	-.0013762	+.0000016831	100	1800	.938	18
200	+2.7652	-.0004893	+.0000019405	100	1200	.967	12
300	+3.1612	-.0034973	+.0000077949	100	900	.947	9
400	+2.8651	-.0019709	+.0000116908	100	600	.998	6
500	+2.6811	-.0004187	+.0000189636	100	400	.999	7
600	+3.2122	-.0072780	+.0000717930	50	225	.996	8
700	+1.0967	+.0513798	-.0001375146	50	150	.979	5

TABLE 13

AVERAGE DELAY -- (SECONDS)

No Acceleration Lane -- Stop-Sign Control

		Ramp Volume -- (100 VPH)						
		1	2	3	4	5	6	7
Shoulder-Lane Volume--(100 VPH)	1	14	14	14	16	19	26	127
	2	14	16	17	21	33	96	
	3	16	17	20	27	95		
	4	17	18	26	49	348		
	5	18	24	33	127			
	6	19	25	46	360			
	7	21	31	63				
	8	23	38	139				
	9	25	40	905				
	10	30	57					
	11	33	85					
	12	38	191					
	13	50	293					
	14	54						
	15	99						
	16	120						
	17	187						
	18	885						

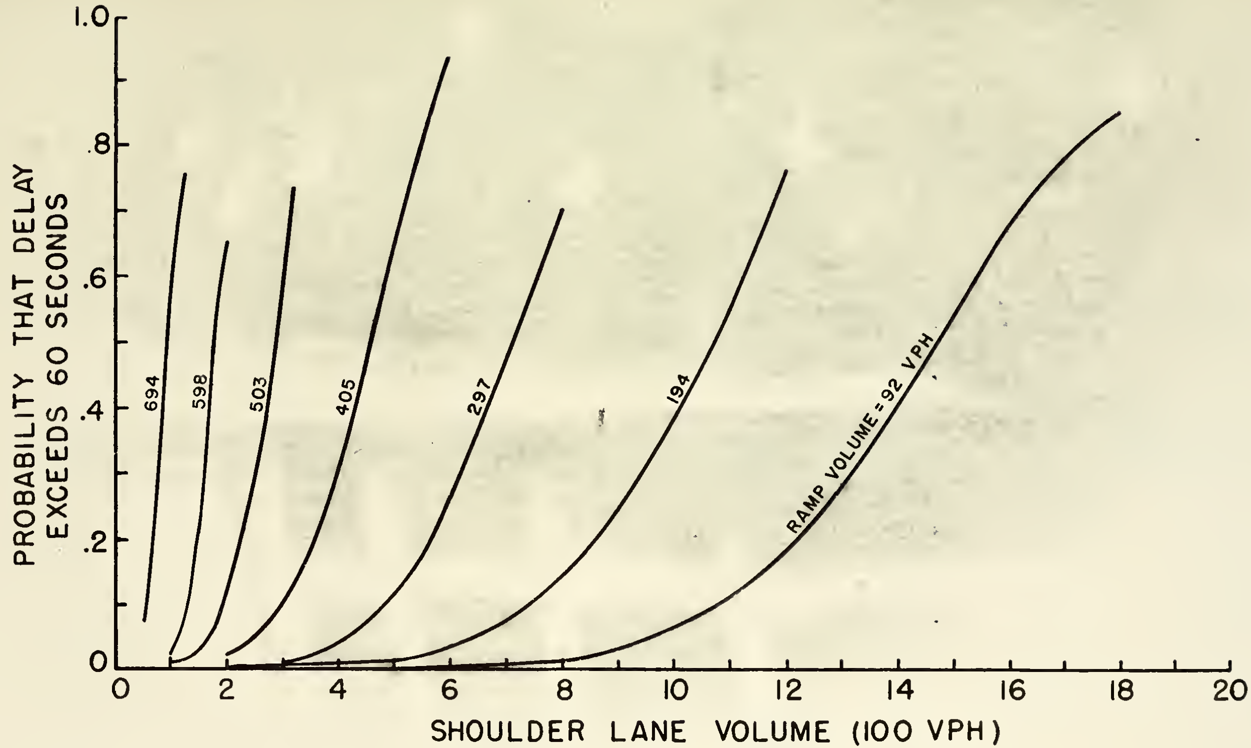

FIG. 19 - PROBABILITY THAT DELAY EXCEEDS 60 SECONDS WITH STOP SIGN CONTROL

TABLE 14

EQUATIONS FOR PREDICTION OF

PROBABILITY THAT DELAY IS GREATER THAN 60 SECONDS

No Acceleration Lane -- Stop-Sign Control

Prediction Model: $y = e^{(a+bx+cx^2)}$ where x is shoulder-lane volume expressed in vehicles per hour.

Ramp Volume (VPH)	Regression Coefficients			Statistical Characteristics			
	a	b	c	Range of Analysis Low x	Range of Analysis High x	R^2	Number of Observations
100	-11.7913	+.0123782	-.0000032853	500	1800	.985	14
200	-9.3662	+.0126359	-.0000042133	200	1200	.936	11
300	-9.5943	+.0205038	-.0000111879	300	800	.969	6
400	-8.0900	+.0249755	-.0000193204	200	600	.996	5
500	-9.4459	+.0493143	-.0000651674	100	400	.995	7
600	-13.3415	+.1252529	-.0003035478	100	225	.985	7
700	-6.6710	+.1034048	-.0004176055	50	120	.941	5

TABLE 15

PROBABILITY THAT DELAY IS GREATER THAN 60 SECONDS

No Acceleration Lane -- Stop-Sign Control

Shoulder-Lane Volume--(100 VPH)	Ramp Volume -- (100 VPH) 1	2	3	4	5	6	7
1	0.00	0.00	0.00	0.00	0.01	0.02	0.55
2	0.00	0.00	0.00	0.02	0.12	0.64	
3	0.00	0.00	0.01	0.09	0.56		
4	0.00	0.00	0.07	0.29	0.96		
5	0.00	0.04	0.11	0.76			
6	0.01	0.03	0.23	0.88			
7	0.01	0.11	0.41				
8	0.02	0.18	0.82				
9	0.04	0.17	1.00				
10	0.08	0.36					
11	0.12	0.53					
12	0.17	0.84					
13	0.28	1.00					
14	0.31						
15	0.53						
16	0.67						
17	0.81						
18	0.97						

parameters of the ramp headway distribution have only been defined for volumes in the range of 100 to 1200 vehicles per hour.

Graphical representations of the empirical models describing the percent of ramp vehicles finding a queue on the ramp, average queue length, average delay, and the probability that a vehicle incurs delay in excess of 60 seconds are shown in Figures 20, 21, 22, and 23, respectively. Summaries of the results of the statistical analyses performed to obtain least-square equations for each of these characteristics are given in Tables 16, 18, 20, and 22. Similar to the stop-sign analyses, multiple R^2's in excess of .960 were obtained for fits to the natural log transformation of an equation of the form,

$$y = e^{(a + bx + cx^2)}$$

The data that are described by these empirical equations are summarized in Tables 17, 19, 21, and 23; but again for convenience of presentation, only the even 100 vehicle per hour data sets are given.

Acceleration Lane--No Sign Control. Although a maximum possible capacity of approximately 1800 vehicles per hour can be realized on a ramp with an acceleration lane and no sign control, provided the shoulder-lane volume is very low, the range of analysis was again restricted to a maximum ramp volume of 1200 vehicles because of the limitations on the ramp-vehicle generator.

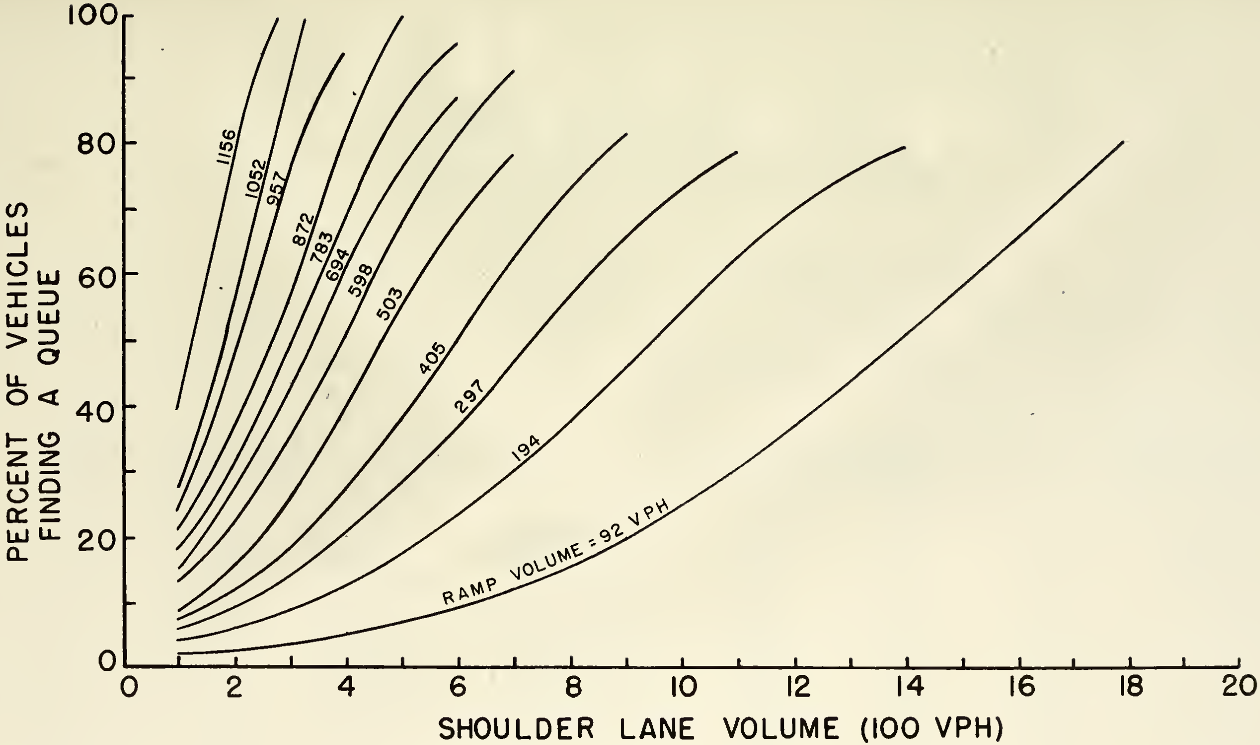

FIG. 20 - PERCENTAGE OF VEHICLES FINDING A QUEUE WITH YIELD SIGN CONTROL

TABLE 16

EQUATIONS FOR PREDICTION OF

PERCENT OF VEHICLES FINDING QUEUE

No Acceleration Lane -- Yield-Sign Control

Prediction Model: $y = 100 \cdot e^{(a+bx+cx^2)}$ where x is shoulder-lane volume expressed in vehicles per hour.

Ramp Volume (VPH)	Regression Coefficients			Statistical Characteristics			
				Range of Analysis			
	a	b	c	Low x	High x	R^2	Number of Observations
100	-4.2801	+.0037031	-.0000008027	100	1800	.987	18
200	-3.6298	+.0045130	-.0000014880	100	1400	.970	14
300	-3.2932	+.0050920	-.0000021042	100	1100	.977	11
400	-3.2012	+.0058612	-.0000028098	100	900	.991	9
500	-3.1236	+.0073832	-.0000046664	100	800	.986	8
600	-2.6466	+.0066111	-.0000042279	100	700	.990	7
700	-2.5234	+.0072951	-.0000055327	100	600	.988	6
800	-2.3602	+.0072031	-.0000055590	100	600	.996	6
900	-2.2251	+.0072706	-.0000056059	100	500	.996	5
1000	-2.3413	+.0103787	-.0000116794	100	450	.994	5
1100	-2.1994	+.0101064	-.0000103447	100	350	.999	4
1200	-1.9683	+.0124299	-.0000191914	100	300	.995	5

TABLE 17

PERCENT OF VEHICLES FINDING QUEUE

No Acceleration Lane -- Yield-Sign Control

		Ramp Volume -- (100 VPH)											
		1	2	3	4	5	6	7	8	9	10	11	12
Shoulder-Lane Volume--(100 VPH)	1	1.4	2.7	4.6	6.2	7.6	11.3	13.8	16.7	19.8	20.2	23.4	32.0
	2	2.8	7.2	10.9	11.7	14.5	24.2	28.2	30.4	31.5	45.3	48.1	66.9
	3	4.8	10.9	15.7	20.1	31.0	34.1	40.3	46.9	53.1	67.5	82.0	99.2
	4	6.0	14.7	24.7	30.1	39.5	46.3	58.8	66.0	79.7	86.8	100.0	100.0
	5	8.3	20.7	25.9	35.0	51.2	64.8	70.0	79.5	96.9	100.0		
	6	9.8	24.7	34.8	45.7	61.7	79.4	91.4	98.7	100.0			
	7	12.8	27.3	40.6	57.5	76.3	94.6	100.0	100.0				
	8	17.1	34.8	53.2	70.5	88.6	100.0						
	9	19.4	40.3	62.9	87.6	100.0							
	10	25.4	46.1	72.6	100.0								
	11	27.9	58.0	87.8									
	12	34.1	65.6										
	13	38.0	78.7										
	14	42.0	94.6										
	15	56.0											
	16	68.3											
	17	78.5											
	18	93.4											

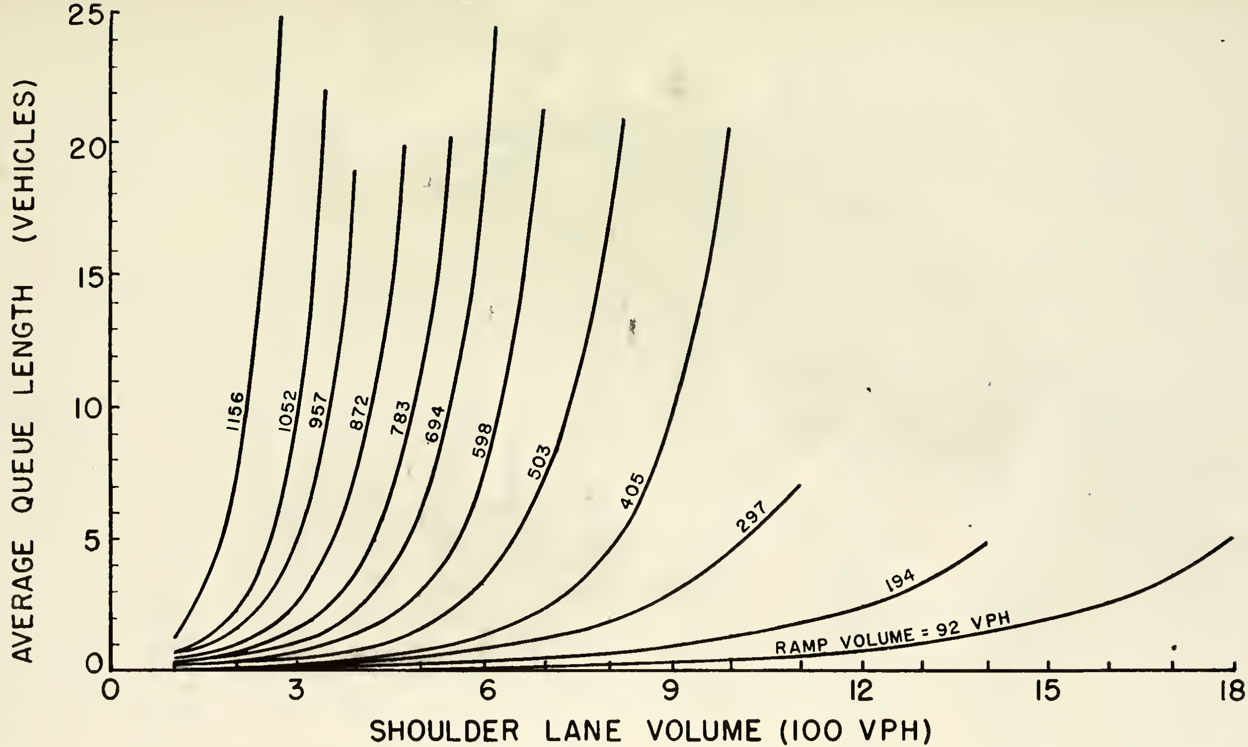

FIG. 21 - AVERAGE QUEUE LENGTH ON RAMP WITH YIELD SIGN CONTROL

TABLE 18

EQUATIONS FOR PREDICTION OF AVERAGE QUEUE LENGTHS

No Acceleration Lane -- Yield-Sign Control

Prediction Model: $y = e^{(a+bx+cx^2)}$ where x is shoulder-lane volume expressed in vehicles per hour.

Ramp Volume (VPH)	Regression Coefficients			Statistical Characteristics			
				Range of Analysis			Number of
	a	b	c	Low x	High x	R^2	Observations
100	-4.2729	+.0033557	-.0000000456	100	1800	.977	18
200	-3.2649	+.0035794	-.0000001103	100	1400	.964	14
300	-3.0580	+.0048794	-.0000002977	100	1100	.973	11
400	-2.5712	+.0032686	-.0000023291	100	1000	.982	10
500	-2.4593	+.0045387	-.0000025817	100	900	.972	9
600	-1.6940	+.0021831	-.0000065882	100	800	.988	8
700	-1.5052	+.0026259	-.0000078505	100	700	.987	7
800	-1.4855	+.0039350	-.0000076947	100	700	.996	7
900	-1.2510	+.0042842	-.0000097527	100	600	.994	6
1000	-1.1467	+.0055615	-.0000116985	100	500	.991	5
1100	-1.4023	+.0081140	-.0000135458	100	400	.999	4
1200	-2.2924	+.0261991	-.0000222119	100	450	.994	8

TABLE 19

AVERAGE QUEUE LENGTHS -- (VEHICLES)

No Acceleration Lane -- Yield-Sign Control

	Ramp Volume -- (100 VPH)											
Shoulder-Lane Volume--(100 VPH)	1	2	3	4	5	6	7	8	9	10	11	12
1	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.3	0.4	0.5	0.5	0.7
2	0.0	0.1	0.1	0.2	0.2	0.4	0.6	0.7	0.9	1.4	1.7	4.6
3	0.1	0.1	0.3	0.3	0.7	0.8	1.0	1.3	1.8	2.8	5.9	26.7
4	0.1	0.2	0.5	0.5	0.9	1.1	2.2	3.2	5.2	16.2	33.6	95.7
5	0.1	0.3	0.4	0.7	1.5	2.7	4.1	7.6	32.0	71.6		
6	0.1	0.4	0.7	1.2	2.9	5.9	14.1	41.2	85.7			
7	0.2	0.5	1.0	1.8	4.2	16.5	80.5	126.2				
8	0.2	0.7	1.5	2.9	12.9	79.7						
9	0.3	0.8	2.9	12.5	57.7							
10	0.4	1.0	4.1	19.7								
11	0.5	1.7	9.2									
12	0.6	2.5										
13	0.7	5.4										
14	1.0	10.5										
15	1.5											
16	2.6											
17	3.6											
18	8.3											

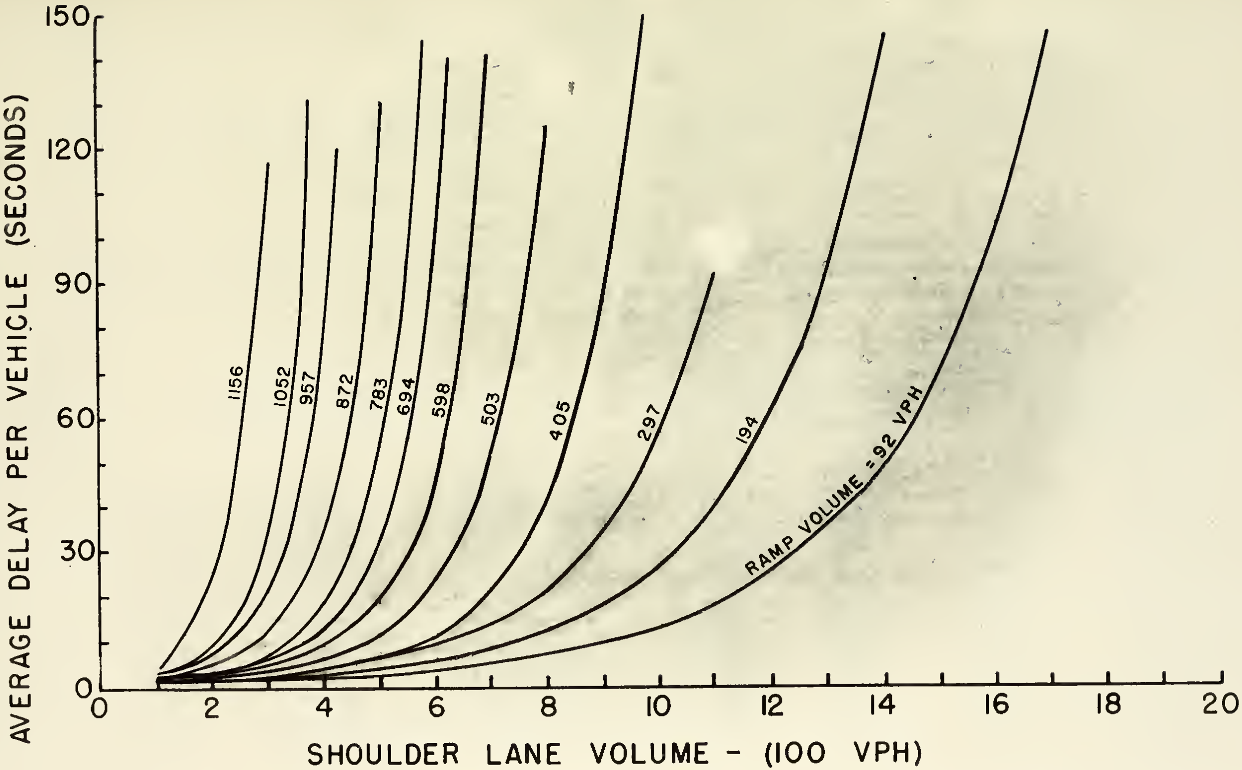

FIG. 22 - AVERAGE DELAY TO RAMP VEHICLES WITH YIELD SIGN CONTROL

TABLE 20

EQUATIONS FOR PREDICTION OF AVERAGE DELAY -- (SECONDS)

No Acceleration Lane -- Yield-Sign Control

Prediction Model: $y = e^{(a+bx+cx^2)}$ where x is shoulder-lane volume expressed in vehicles per hour.

Ramp Volume (VPH)	Regression Coefficients			Statistical Characteristics			
				Range of Analysis			Number of
	a	b	c	Low x	High x	R^2	Observations
100	-0.0969	+.0022760	+.0000004194	100	1800	.984	18
200	+0.0931	+.0025321	+.0000006884	100	1400	.973	14
300	-0.1598	+.0036479	+.0000005528	100	1100	.984	11
400	+0.0532	+.0024242	+.0000027514	100	1000	.981	10
500	+0.1778	+.0024766	+.0000041782	100	900	.975	9
600	+0.5665	+.0009040	+.0000076655	100	800	.988	8
700	+0.6343	+.0010002	+.0000094279	100	700	.986	7
800	+0.5380	+.0019045	+.0000101179	100	600	.990	6
900	+0.6158	+.0028395	+.0000113563	100	600	.996	6
1000	+0.5615	+.0041011	+.0000137510	100	500	.994	5
1100	+0.4076	+.0056497	+.0000167166	100	400	.999	4
1200	-0.2721	+.0189543	-.0000071903	100	400	.994	7

TABLE 21

AVERAGE DELAY -- (SECONDS)

No Acceleration Lane -- Yield-Sign Control

Shoulder-Lane Volume--(100 VPH)	Ramp Volume -- (100 VPH) 1	2	3	4	5	6	7	8	9	10	11	12
1	1	1	1	1	1	2	2	2	2	3	3	3
2	2	2	2	2	2	3	4	4	5	6	7	16
3	2	3	3	3	5	6	6	7	9	13	23	87
4	3	4	5	6	7	8	12	16	24	64	127	344
5	4	6	6	7	12	18	24	36	137	324		
6	5	7	9	11	21	39	75	204	434			
7	6	9	13	17	33	104	486					
8	8	12	17	27	93	557						
9	10	15	35	111	446							
10	14	20	50	180								
11	17	32	115									
12	23	48										
13	27	100										
14	39	207										
15	57											
16	94											
17	138											
18	331											

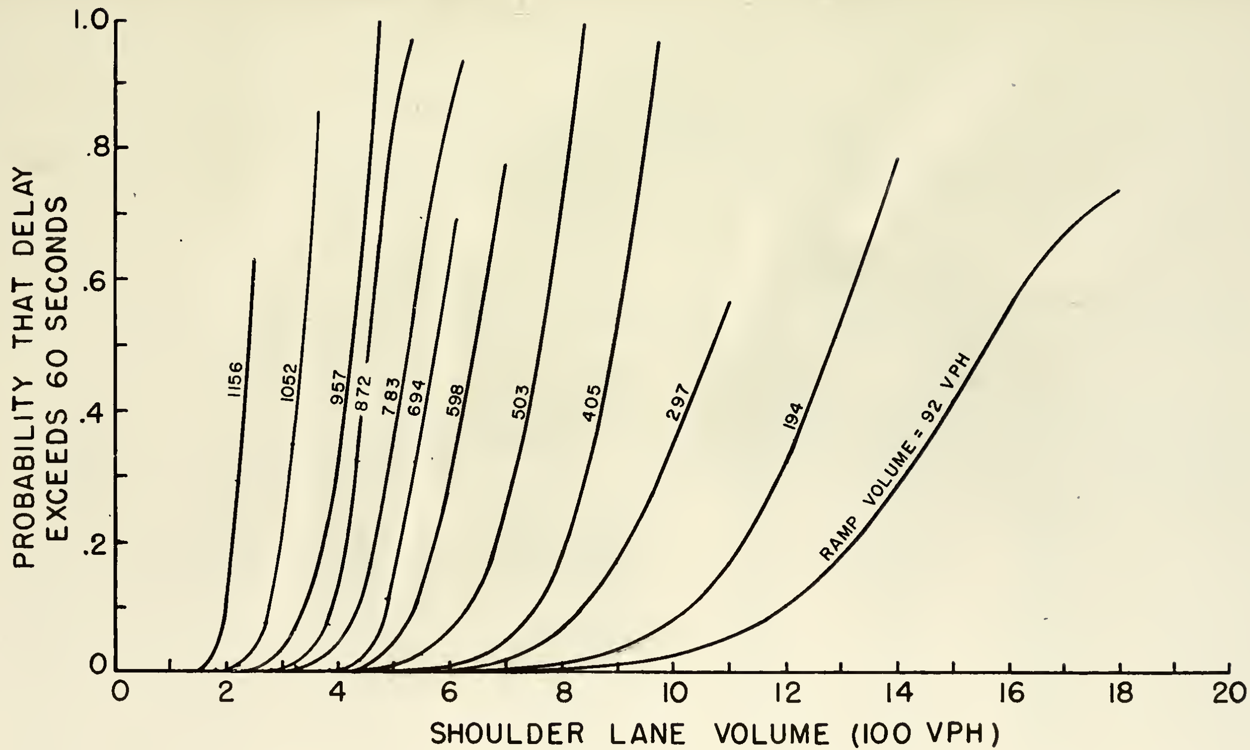

FIG. 23 - PROBABILITY THAT DELAY EXCEEDS 60 SECONDS WITH YIELD SIGN CONTROL

TABLE 22

EQUATIONS FOR PREDICTION OF

PROBABILITY THAT DELAY IS GREATER THAN 60 SECONDS

No Acceleration Lane -- Yield-Sign Control

Prediction Model: $y = e^{(a+bx+cx^2)}$ where x is shoulder-lane volume expressed in vehicles per hour.

Ramp Volume (VPH)	Regression Coefficients			Statistical Characteristics			
				Range of Analysis			Number of
	a	b	c	Low x	High x	R^2	Observations
100	-16.1550	+.0170741	-.0000045908	700	1800	.988	12
200	-15.9561	+.0191254	-.0000056410	600	1400	.988	9
300	-17.5748	+.0271073	-.0000105851	500	1100	.988	7
400	-21.3262	+.0370901	+.0000156363	500	1000	.987	6
500	-19.3923	+.0393628	+.0000194069	400	850	.998	6
600	-29.0753	+.0781986	+.0000528842	400	750	.986	5
700	-47.3614	+.1526573	-.0001346453	400	650	.981	6
800	-21.6138	+.0675914	+.0000529782	300	625	.997	5
900	-28.8463	+.1063333	-.0000980491	300	550	.999	6
1000	-14.7238	+.0494355	+.0000386172	200	500	.956	4
1100	-21.5913	+.1035501	-.0001235440	200	400	.999	5
1200	-26.5800	+.1917022	-.0003487793	150	300	.999	4

TABLE 23

PROBABILITY THAT DELAY IS GREATER THAN 60 SECONDS

No Acceleration Lane -- Yield-Sign Control

Shoulder-Lane Volume--(100 VPH)	Ramp Volume -- (100 VPH)											
	1	2	3	4	5	6	7	8	9	10	11	12
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.07	0.80
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.08	0.37	0.83	1.00
5	0.00	0.00	0.00	0.00	0.01	0.06	0.13	0.22	0.71	1.00		
6	0.00	0.00	0.01	0.01	0.08	0.22	0.52	0.80	1.00			
7	0.00	0.01	0.03	0.04	0.20	0.69	1.00	1.00				
8	0.00	0.01	0.04	0.12	0.67	1.00						
9	0.02	0.03	0.17	0.68	1.00							
10	0.03	0.07	0.33	0.98								
11	0.06	0.16	0.62									
12	0.10	0.27										
13	0.14	0.56										
14	0.23	0.83										
15	0.36											
16	0.52											
17	0.69											
18	0.91											

The graphical representations of the empirical models describing the percent of ramp vehicles finding a queue on the ramp, average queue length, average delay, and the probability that a vehicle incurs delay in excess of 60 seconds are presented in Figures 24, 25, 26, and 27, respectively. Summaries of the statistical analyses, made in order to obtain least-square estimates of the parameters of the empirical models describing these characteristics, are shown in Tables 24, 26, 28, and 30. All of the relationships were fitted to the same model used previously for the stop-sign and yield-sign controlled ramps; and again, the amounts of variability (R^2) in the logarithms of the dependent variables that were described by the transformed models were in excess of 0.950 in all cases.

The majority of the data that are described by these graphical and mathematical models are summarized in Tables 25, 27, 29, and 31, but the data sets for volume conditions intermediate between the even 100 vehicle per hour intervals were excluded for convenience of presentation.

Practical Capacity Analysis

Numerical Limits for Practical Capacity

The empirical models describing the probability that a vehicle will incur delay in excess of 60 seconds were utilized to define the practical capacities of the three ramp designs. These models were solved at each level of ramp volume to establish the shoulder-lane volume at which the probability of delay

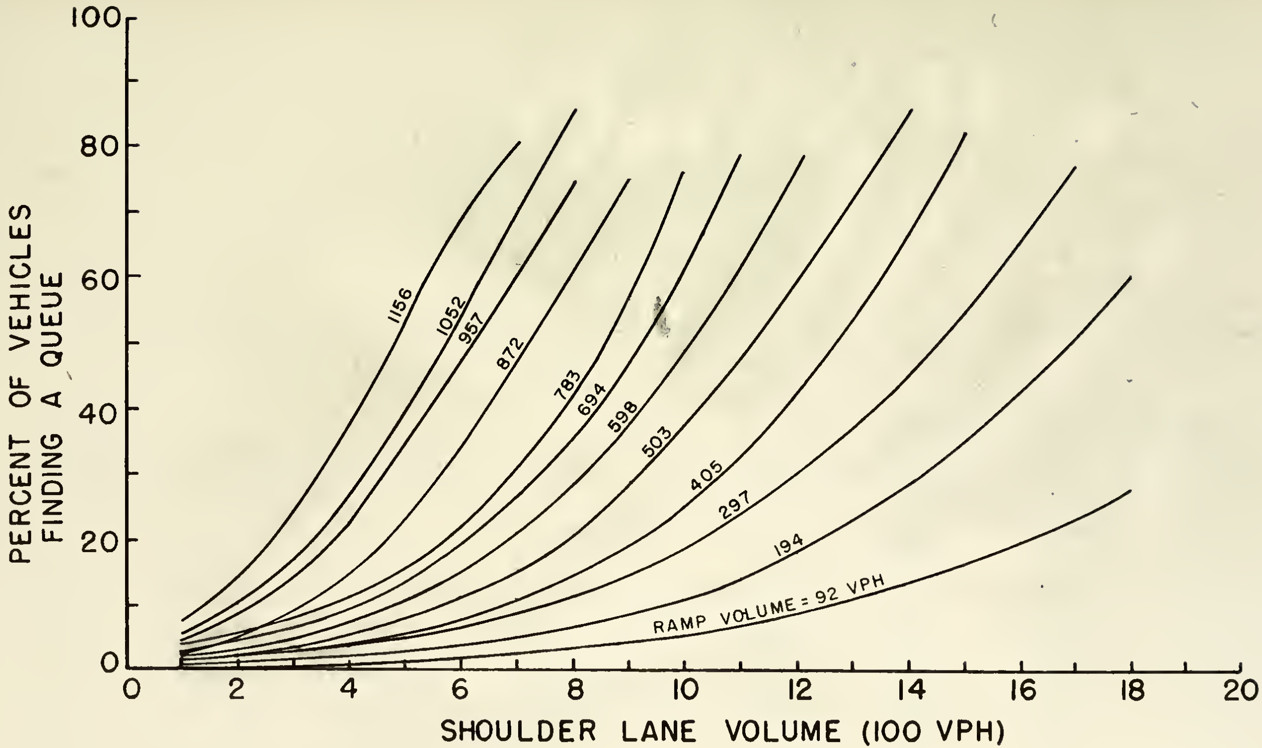

FIG. 24 - PERCENTAGE OF VEHICLES FINDING A QUEUE WITH ACCELERATION LANE

TABLE 24

EQUATIONS FOR PREDICTION OF

PERCENT OF VEHICLES FINDING QUEUE

Acceleration Lane -- No Sign Control

Prediction Model: $y = 100 \cdot e^{(a+bx+cx^2)}$ where x is shoulder-lane volume expressed in vehicles per hour.

Ramp Volume (VPH)	Regression Coefficients			Statistical Characteristics			
				Range of Analysis			Number of
	a	b	c	Low x	High x	R^2	Observations
100	-6.3814	+.0043315	-.0000008418	100	1800	.950	18
200	-5.2680	+.0036588	-.0000005607	100	1800	.974	18
300	-4.5901	+.0034575	-.0000005320	100	1700	.990	17
400	-4.6350	+.0038877	-.0000006157	100	1500	.998	15
500	-4.7330	+.0049777	-.0000012171	100	1400	.985	14
600	-4.4088	+.0049218	-.0000012182	100	1300	.982	13
700	-4.0760	+.0046732	-.0000010735	100	1200	.989	12
800	-3.6181	+.0037732	-.0000004237	100	1100	.998	11
900	-4.4158	+.0075284	-.0000032691	100	1000	.996	10
1000	-3.8273	+.0073295	-.0000036348	100	900	.987	9
1100	-3.5488	+.0069249	-.0000033516	100	900	.983	9
1200	-3.3013	+.0077166	-.0000047185	100	800	.968	8

TABLE 25

PERCENT OF VEHICLES FINDING QUEUE

Acceleration Lane -- No Sign Control

Shoulder-Lane Volume--(100 VPH)	Ramp Volume -- (100 VPH) 1	2	3	4	5	6	7	8	9	10	11	12
1	0.0	0.4	1.0	1.4	1.0	1.3	2.2	3.9	2.3	3.2	4.0	5.2
2	0.5	1.7	2.1	1.9	2.9	4.1	4.8	4.8	3.9	8.5	10.8	16.1
3	0.8	1.4	3.4	2.8	3.2	5.6	4.9	7.7	7.3	14.7	17.6	24.8
4	1.2	2.3	4.0	4.2	5.0	6.5	10.7	11.2	15.9	20.9	24.0	32.1
5	1.8	3.3	5.8	6.2	9.3	9.9	12.8	15.3	21.4	28.4	33.0	38.9
6	1.7	4.2	7.2	8.4	12.9	14.8	20.1	22.2	30.1	40.3	45.3	67.5
7	2.7	4.3	8.3	10.9	15.7	21.8	24.1	27.1	43.0	62.1	70.2	78.4
8	3.0	8.9	9.5	13.6	19.1	25.8	32.1	44.6	63.5	72.9	85.6	90.8
9	4.7	8.8	14.5	19.9	28.8	34.4	48.3	53.8	76.1	88.2	99.7	
10	4.8	10.4	18.3	22.7	33.5	41.5	58.2	77.1	84.5	100.0		
11	4.4	10.4	24.0	30.8	39.6	71.1	79.9	99.4	100.0			
12	9.3	18.2	27.3	43.8	49.5	74.8	99.6	100.0				
13	7.9	18.4	34.5	54.1	80.4	95.0						
14	11.3	28.5	41.3	63.0	97.3							
15	16.0	34.4	56.7	88.6	100.0							
16	21.1	42.7	63.3	100.0								
17	26.6	54.6	86.8									
18	35.0	65.2	100.0									

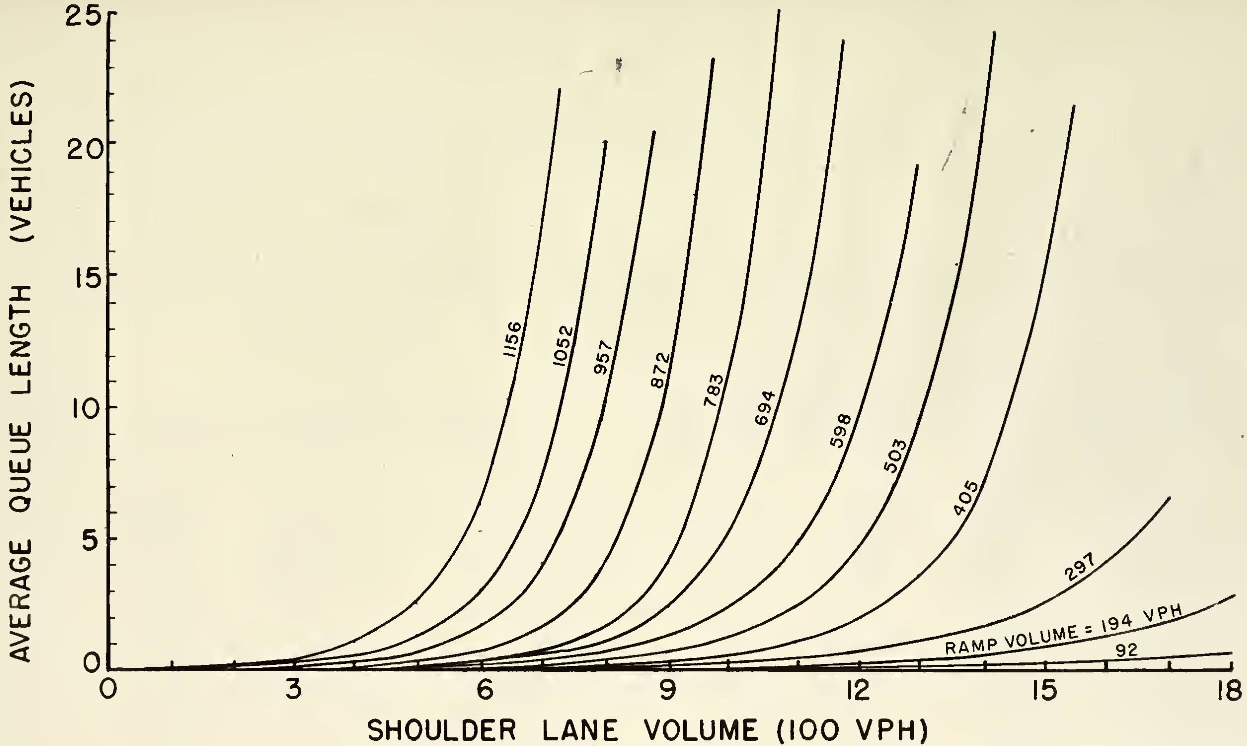

FIG. 25 - AVERAGE QUEUE LENGTH ON RAMP WITH ACCELERATION LANE

TABLE 26

EQUATIONS FOR PREDICTION OF AVERAGE QUEUE LENGTHS

Acceleration Lane -- No Sign Control

Prediction Model: $y = e^{(a+bx+cx^2)}$ where x is shoulder-lane volume expressed in vehicles per hour.

Ramp Volume (VPH)	Regression Coefficients a	b	c	Statistical Characteristics: Range of Analysis Low x	High x	R^2	Number of Observations
100	-5.0258	+.0016410	+.0000005153	200	1800	.978	17
200	-4.6655	+.0022476	+.0000005141	200	1800	.978	17
300	-4.4841	+.0028177	+.0000005433	100	1700	.988	17
400	-4.3162	+.0019374	+.0000018261	100	1600	.974	16
500	-4.2762	+.0027761	+.0000017289	100	1500	.981	15
600	-4.4491	+.0043213	+.0000010611	100	1300	.983	13
700	-3.8462	+.0027600	+.0000027415	100	1200	.989	12
800	-3.0714	+.0004599	+.0000050207	100	1200	.994	12
900	-4.1394	+.0047775	+.0000027603	100	1100	.988	11
1000	-3.5794	+.0053980	+.0000024726	100	1000	.988	10
1100	-3.1336	+.0051631	+.0000031242	100	900	.991	9
1200	-3.0124	+.0065285	+.0000026169	100	800	.984	8

TABLE 27

AVERAGE QUEUE LENGTHS -- (VEHICLES)

Acceleration Lane -- No Sign Control

Shoulder-Lane Volume--(100 VPH)	Ramp Volume -- (100 VPH) 1	2	3	4	5	6	7	8	9	10	11	12
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.2	0.3
3	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.3	0.4
4	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.4	0.6	0.8
5	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2	0.3	0.6	0.9	1.3
6	0.0	0.0	0.1	0.1	0.2	0.3	0.4	0.4	1.1	1.2	2.1	5.5
7	0.0	0.1	0.1	0.2	0.2	0.4	0.5	0.6	1.3	3.8	6.7	15.5
8	0.0	0.1	0.1	0.2	0.4	0.7	0.8	2.0	3.3	7.3	15.4	41.9
9	0.1	0.1	0.2	0.4	0.8	1.1	2.0	3.5	6.3	21.4	61.8	
10	0.1	0.2	0.3	0.4	0.9	1.8	3.9	7.3	26.3	98.7		
11	0.1	0.2	0.6	0.8	1.5	4.8	10.3	29.5	119.1			
12	0.1	0.3	0.7	1.5	2.6	6.3	38.4	134.3				
13	0.1	0.3	1.0	2.4	8.0	28.3						
14	0.1	0.6	1.4	3.8	17.4							
15	0.2	0.9	3.0	2.6	81.6							
16	0.3	1.1	3.3	74.8								
17	0.5	2.1	8.5									
18	0.8	2.6	67.8									

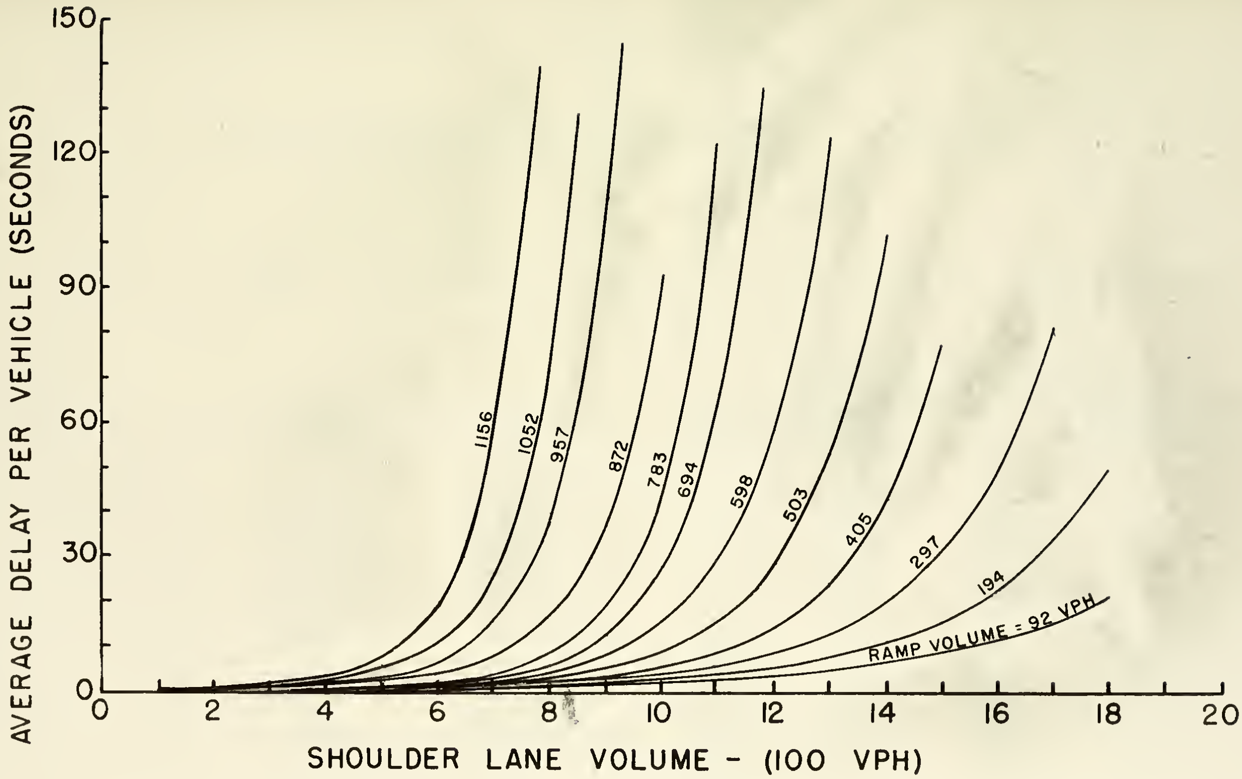

FIG. 26 - AVERAGE DELAY TO RAMP VEHICLES WITH ACCELERATION LANE

TABLE 28

EQUATIONS FOR PREDICTION OF AVERAGE DELAY -- (SECONDS)

Acceleration Lane -- No Sign Control

Prediction Model: $y = e^{(a+bx+cx^2)}$ where x is shoulder-lane volume expressed in vehicles per hour.

Ramp Volume (VPH)	Regression Coefficients			Statistical Characteristics			
				Range of Analysis			
	a	b	c	Low x	High x	R^2	Number of Observations
100	-2.1045	+.0029398	-.0000000386	100	1800	.985	18
200	-1.6750	+.0023434	+.0000004250	100	1800	.990	18
300	-1.6785	+.0023707	+.0000007087	100	1700	.989	17
400	-1.4401	+.0016767	+.0000014566	100	1500	.987	15
500	-1.5498	+.0021741	+.0000015970	100	1400	.987	14
600	-1.4659	+.0019993	+.0000021832	100	1300	.985	13
700	-1.1070	+.0005302	+.0000039077	100	1200	.991	12
800	-0.9499	+.0003271	+.0000044638	100	1100	.995	11
900	-1.4987	+.0027609	+.0000032714	100	1000	.989	10
1000	-1.0421	+.0018696	+.0000050159	100	1000	.992	10
1100	-0.9161	+.0021628	+.0000054528	100	900	.993	9
1200	-0.7589	+.0024525	+.0000063174	100	800	.991	8

TABLE 29

AVERAGE DELAY -- (SECONDS)

Acceleration Lane -- No Sign Control

Shoulder-Lane Volume--(100 VPH)	Ramp Volume -- (100 VPH) 1	2	3	4	5	6	7	8	9	10	11	12
1	0	0	0	0	0	0	0	0	0	0	0	1
2	0	0	0	0	0	0	0	0	0	1	1	1
3	0	0	1	1	1	1	1	1	1	1	1	2
4	0	1	1	1	1	1	1	1	1	2	2	3
5	1	1	1	1	1	1	1	1	2	3	3	4
6	1	1	1	1	2	2	2	2	5	5	8	18
7	1	1	1	2	2	3	3	4	6	15	23	52
8	1	2	2	2	3	4	5	9	14	28	55	153
9	2	2	3	4	6	7	11	17	27	89	247	
10	2	3	3	4	7	11	21	36	117	442		
11	2	3	7	7	11	28	53	143	574			
12	4	6	8	13	19	40	221	734				
13	4	6	12	21	57	175						
14	6	11	16	34	134							
15	8	15	31	122	697							
16	11	22	41	728								
17	17	39	112									
18	28	52	876									

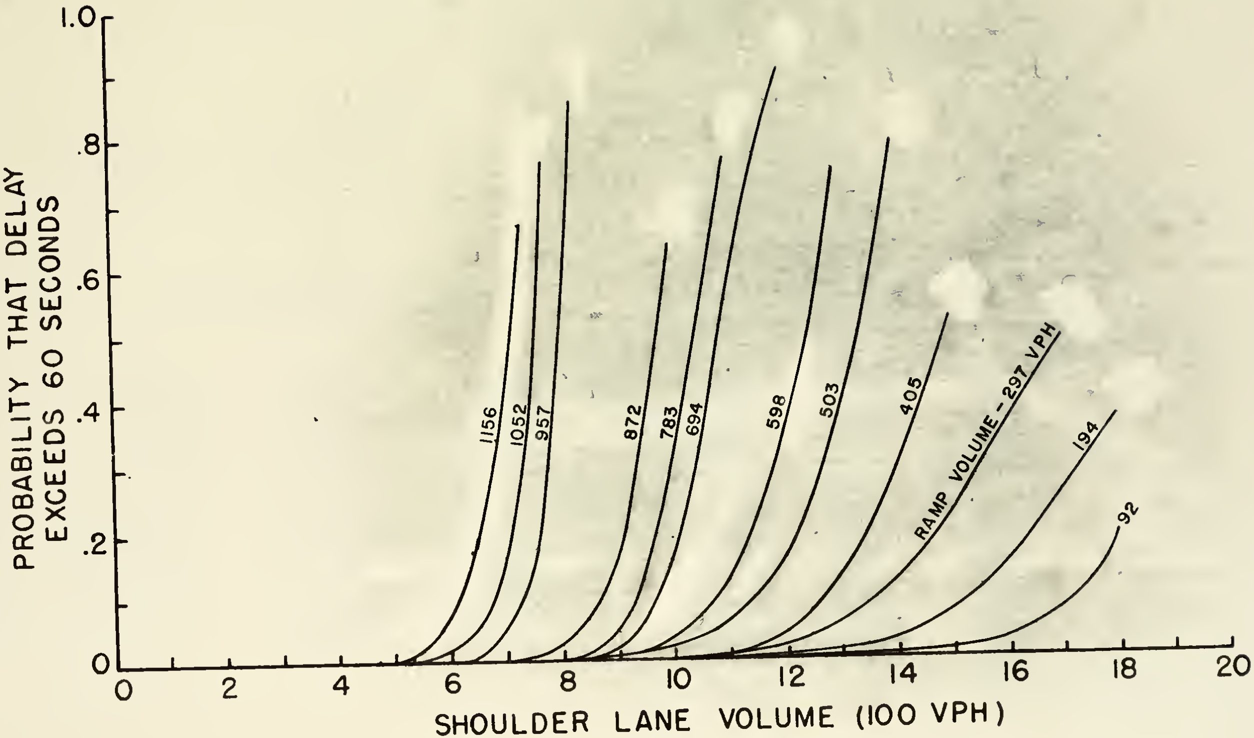

FIG. 27 - PROBABILITY THAT DELAY EXCEEDS 60 SECONDS
ACCELERATION LANE

TABLE 30

EQUATIONS FOR PREDICTION OF

PROBABILITY THAT DELAY IS GREATER THAN 60 SECONDS

Acceleration Lane -- No Sign Control

Prediction Model: $y = e^{(a+bx+cx^2)}$ where x is shoulder-lane volume expressed in vehicles per hour.

Ramp Volume (VPH)	Regression Coefficients			Statistical Characteristics			
				Range of Analysis			
	a	b	c	Low x	High x	R^2	Number of Observations
100	-12.7287	+.0026419	+.0000019410	1200	1800	.927	7
200	-32.2409	+.0318443	-.0000080515	1100	1800	.997	8
300	-27.9335	+.0298356	-.0000081325	1000	1700	.937	8
400	-38.0136	+.0454645	-.0000137083	1000	1500	.953	6
500	-19.3308	+.0201150	-.0000046270	800	1400	.944	7
600	-31.4166	+.0417297	-.0000136855	800	1200	.995	5
700	-56.4630	+.0927711	-.0000381728	800	1200	.989	5
800	-59.8336	+.1030377	-.0000444457	800	1100	.991	4
900	-42.7534	+.0738793	-.0000315796	700	1000	.999	4
1000	-39.8221	+.0778939	-.0000361358	600	850	.995	5
1100	-21.1578	+.0339636	-.0000090505	500	800	.999	5
1200	-41.9321	+.1061389	-.0000674651	500	750	.999	6

TABLE 31

PROBABILITY THAT DELAY IS GREATER THAN 60 SECONDS

Acceleration Lane -- No Sign Control

Shoulder-Lane Volume--(100 VPH)	Ramp Volume -- (100 VPH) 1	2	3	4	5	6	7	8	9	10	11	12
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.06
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.09	0.32
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.18	0.42	0.57
9	0.00	0.00	0.00	0.00	0.02	0.01	0.03	0.06	0.16	0.41	0.85	
10	0.00	0.00	0.00	0.00	0.02	0.03	0.11	0.18	0.59	1.00		
11	0.00	0.00	0.02	0.02	0.03	0.14	0.42	0.79	1.00			
12	0.00	0.00	0.02	0.04	0.10	0.29	0.97	1.00				
13	0.00	0.01	0.05	0.09	0.40	0.72						
14	0.00	0.04	0.07	0.22	0.82							
15	0.02	0.07	0.21	0.68	1.00							
16	0.03	0.12	0.30	1.00								
17	0.08	0.26	0.64									
18	0.15	0.34	1.00									

in excess of 60 seconds was 0.15. The resulting ramp volume, shoulder-lane volume data sets described the relationship between practical ramp capacity and shoulder-lane volume. These data sets are plotted for each of the three ramp designs in Figure 28. The curves drawn through these points are least-square fits to a model of the form,

$$y = e^{(a + bx + cx^2)} .$$

The complete analyses are summarized in Table 32.

A comparison of the practical and possible capacities defined in the study revealed that the practical capacities of stop-sign and yield-sign controlled ramps vary from about 30 percent of possible capacity at high shoulder-lane volumes, to about 90 percent of possible capacity at low shoulder-lane volumes. In the case of the ramp with an acceleration lane, the comparison indicated that practical capacity varied from approximately 50 percent of possible at high shoulder-lane volumes to nearly 110 percent of possible capacity at the lowest shoulder-lane volume studied. It is not reasonable for practical capacity to exceed possible capacity; but the discrepancy can be explained.

This discrepancy in the results obtained from the queuing model and the simulator resulted from an operating condition that was assumed to exist and was built into the queuing model. The assumed condition did not always materialize, however, when the possible-capacity levels predicted by the queuing model were reproduced by the simulator. The operating restriction that was

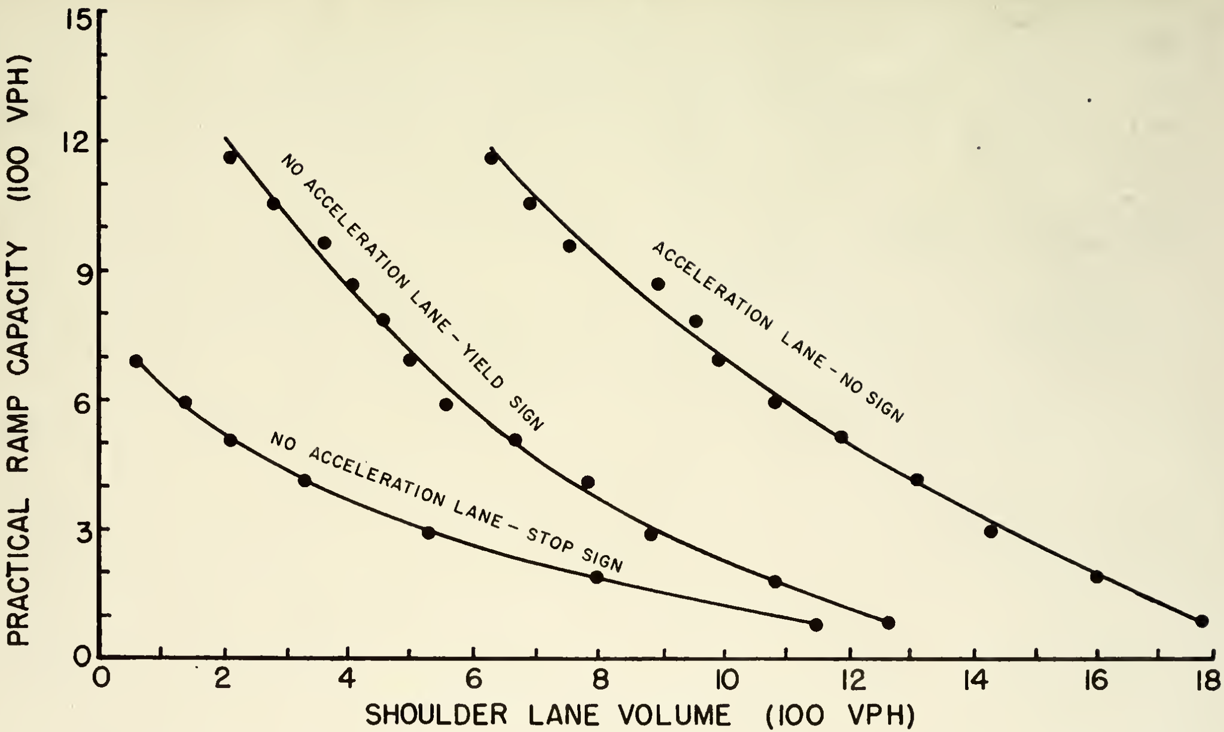

FIG.28-PRACTICAL CAPACITIES OF FREEWAY ON-RAMPS

TABLE 32

SUMMARY OF LEAST-SQUARE EQUATIONS FOR PREDICTING PRACTICAL CAPACITIES OF FREEWAY ON-RAMPS

Prediction Model: $y = e^{(a+bx+cx^2)}$*

Regression Coefficients			Statistical Characteristics			
			Limits of Analysis-x			
a	b	c	Low	High	R^2	Number of Observations
No Acceleration Lane and Stop-Sign Control						
+6.5781	-0.0014546	-0.0000002356	63	1150	.986	7
No Acceleration Lane and Yield-Sign Control						
+7.2901	-0.0009507	-0.0000009338	203	1267	.996	12
Acceleration Lane and No Sign Control						
+6.9814	+0.0008034	-0.0000012041	633	1783	.996	12

* y = Practical Capacity -- vph
x = Shoulder-Lane Volume -- vph

imposed by the queuing model required every queue of ramp vehicles utilizing the capacity available in each single shoulder-lane gap, to depart from a stopped condition. As a consequence the first driver in each queue based his gap-acceptance decision on the more restrictive gap-acceptance model for stopped, first-in-line vehicles. The simulator, however, did not absolutely require that every queue depart from a stopped condition. Even as possible capacity was approached, the driver had the option to modify his speed in the ramp-acceleration lane area in such a manner as to delay his arrival time at the entry point to the shoulder lane. By effecting this moving delay the driver was able to take advantage of the less restrictive, no-stop, gap-acceptance model. In real life, drivers undoubtedly follow this practice. The results suggest that the possible capacities of ramps with acceleration lanes and no sign control are actually a little higher than indicated by the queuing model.

Although there were no instances in which the practical capacities exceeded the possible capacities of ramps with no acceleration lanes and yield-sign control, the discrepancies in the above case led to an investigation of the adequacy of the assumed operating conditions for this latter type of ramp. A review of the vehicle-counter logs kept by the yield-sign simulator monitor revealed, however, that even though absolute stops were not required with yield control, the maneuver distance available without an acceleration lane was not long

enough to permit moving delays. As a consequence the necessary stop condition was forced by the traffic itself at those volume levels approaching possible capacity as defined by the queuing model.

Of course, there is no question as to whether or not the necessary stop condition is satisfied on ramps with no acceleration lanes and stop-sign control. A stop is mandatory for every single vehicle leaving the ramp when this type of sign control is utilized.

Queuing Conditions at Practical Capacity

The average queue length models were solved and percentile queue data were evaluated at practical-capacity volume conditions. The various queue-length estimates that were obtained are plotted as functions of shoulder-lane volume in Figures 29, 30, and 31, respectively, for ramps with no acceleration lane and stop-sign control, no acceleration lane and yield-sign control, and an acceleration with no sign control. Although there was relatively little scatter in the data describing the queuing conditions on the stop-sign controlled ramp, a statistical analysis was performed for the purpose of deriving prediction models. An empirical equation of the form,

$$y = e^{(a + bx)},$$

was fitted to the data describing average queue lengths using the method of least squares. Equations of the form,

$$y = e^{\left(\frac{1}{a + bx + cx^2}\right)},$$

were derived for prediction of 85th, 90th and 95th percentile queue lengths. The results of the statistical analyses are presented in Table 33, where it should be noted that the multiple R^2's (r^2 in the case of the average queue length model) for the transformed equations were all equal to or greater than 0.967.

The various practical-capacity queuing characteristics for the ramp with yield-sign control and the ramp with an acceleration lane were described by empirical, least-square equations of the form,

$$y = e^{(a + bx)},$$

and the results are presented in Table 34. Because of scatter in the average queue length data the r^2 values were only 0.916 and 0.883 for the yield-sign control condition and the acceleration-lane condition, respectively.

An analysis of comparable queue length indices for the three design-control combinations at various shoulder-lane volumes revealed that queue lengths at practical-capacity conditions vary directly with the practical capacity of the ramp. At any given shoulder-lane volume the queues at practical-capacity conditions are longest with an acceleration lane and no sign control; the shortest queues form on the ramps with no acceleration lane and

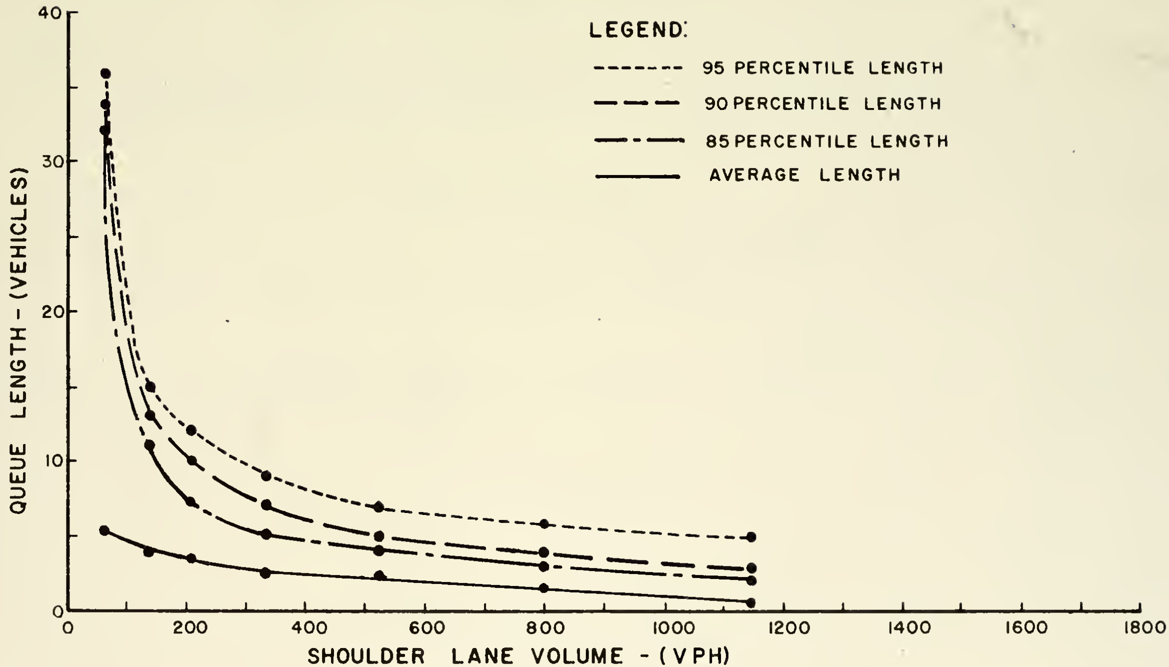

FIG. 29 - QUEUE LENGTHS AT PRACTICAL CAPACITY WITH STOP-SIGN CONTROL

TABLE 33

SUMMARY OF LEAST-SQUARE EQUATIONS FOR PREDICTING QUEUE CHARACTERISTICS UNDER PRACTICAL CAPACITY CONDITIONS ON ON-RAMPS WITH NO ACCELERATION LANE AND STOP-SIGN CONTROL

Average Queue Prediction Model: $y = e^{(a+bx)}$ *

Percentile Queue Prediction Model: $y = e^{(1/(a+bx+cx^2))}$ *

Variable Predicted	Regression Coefficients			Statistical Characteristics			
				Limits of Analysis-x			
	a	b	c	Low	High	R^2	Number of Observations
Avg. Queue	+1.7006	-0.0017448		63	1150	.967(r^2)	7
85% Queue	+0.3214	+0.0006068	+0.0000002942	63	1150	.976	7
90% Queue	+0.2714	+0.0007434	-0.0000001732	63	1150	.988	7
95% Queue	+0.2738	+0.0005952	-0.00000026[illegible]3	63	1150	.972	7

* y = Queue Variable Predicted -- vehicles
x = Shoulder-Lane Volume -- vph

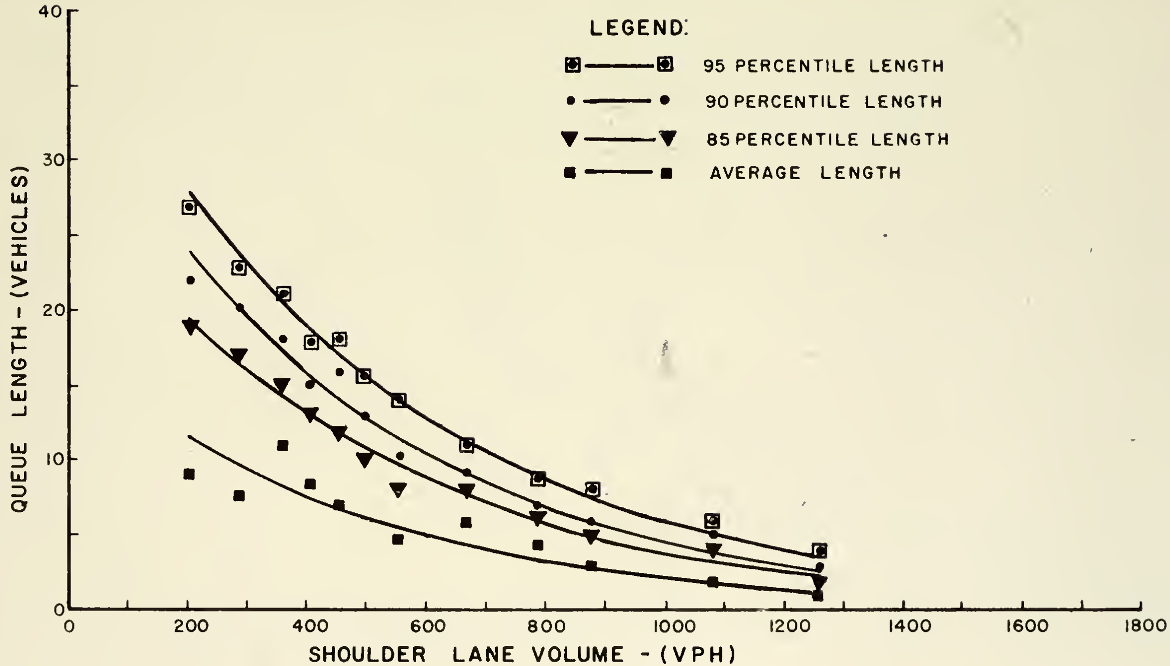

FIG.30-QUEUE LENGTHS AT PRACTICAL CAPACITY WITH YIELD-SIGN CONTROL

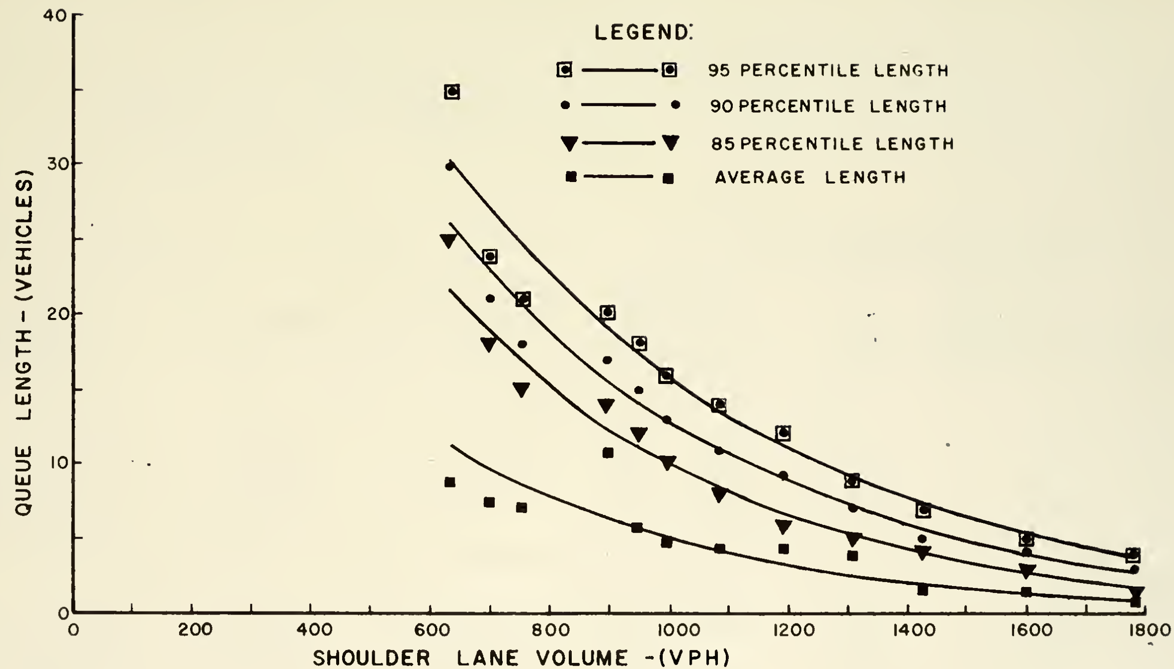

FIG.31-QUEUE LENGTHS AT PRACTICAL CAPACITY WITH ACCELERATION LANE

TABLE 34

SUMMARY OF LEAST-SQUARE EQUATIONS FOR PREDICTING QUEUE CHARACTERISTICS UNDER PRACTICAL CAPACITY CONDITIONS ON ON-RAMPS WITH NO ACCELERATION AND YIELD-SIGN CONTROL AND ON ON-RAMPS WITH AN ACCELERATION LANE AND NO SIGN CONTROL

Prediction Model: $y = e^{(a+bx)}$ *

Variable Predicted	Regression Coefficients a	Regression Coefficients b	Limits of Analysis-x Low	Limits of Analysis-x High	r^2	Number of Observations
					Statistical Characteristics	
No Acceleration Lane and Yield-Sign Control						
Avg. Queue	+2.8634	-0.0021425	203	1267	.916	12
85% Queue	+3.3754	-0.0020187	203	1267	.980	12
90% Queue	+3.6052	-0.0021090	203	1267	.964	12
95% Queue	+3.7252	-0.0019438	203	1267	.984	12
Acceleration Lane and No Sign Control						
Avg. Queue	+3.7821	-0.0021669	633	1783	.883	12
85% Queue	+4.4148	-0.0021100	633	1783	.988	12
90% Queue	+4.4861	-0.0019356	633	1783	.986	12
95% Queue	+4.5476	-0.0017941	633	1783	.983	12

* y = Queue Variable Predicted -- vehicles
x = Shoulder-Lane Volume -- vph

stop-sign control. This outcome is quite reasonable. A ramp with an acceleration lane and no sign control feeds ramp traffic into the shoulder lane at a higher rate than a ramp with no acceleration lane and yield-sign control. In the case of ramps with no acceleration lane, yield-sign control effects a much higher ramp flow rate than does stop-sign control. Thus, although queue lengths at practical ramp capacity vary with the type of control for any set level of shoulder-lane volume, these queues are dissipated at rates directly related to their length; and the delay characteristics for the three design-control conditions are similar.

SUMMARY AND CONCLUSIONS

1. Objective criteria were established for the measurement of the possible and practical capacities of freeway on-ramps. These criteria were stated in definition form.
   a. Possible capacity of a freeway on-ramp is the maximum number of vehicles that can enter the through highway during one hour under the prevailing conditions with a continual backlog of waiting vehicles.
   b. Practical capacity of a freeway on-ramp is the maximum number of vehicles that can enter the through highway during one hour with 85 percent of the drivers being able to leave the ramp without being delayed more than 60 seconds.
2. The micro-aspects of freeway on-ramp areas and their traffic were modeled in the mathematical mode, within the present understanding of traffic flow theory. In some cases, empirical estimates were substituted for presently undefined functional relationships.
3. Rules of operation were established for the on-ramp area that provided a framework within which the models describing micro-aspects were assembled as functional systems.

a. The rules for operation of the ramp system at possible capacity were implied by the definition of possible capacity. These rules provided for the development of a deterministic queuing model that adequately describes the possible capacity of ramps with no acceleration lane and either stop- or yield-sign control. This queuing model predicted possible capacities that were slightly low in the case of ramps with an acceleration lane and no sign control.

b. More general rules were designed and implemented as control mechanisms in a computer-oriented ramp simulator. A wide range of ramp and shoulder-lane volume combinations were realistically generated by this model. Traffic monitors constructed as integral parts of the simulator measured and recorded several indices of traffic performance. The most important of these were the percent of vehicles that found queues on the ramp, average and percentile queue lengths, average delay, and the probability that delay exceeds 60 seconds.

4. Statistical models were derived to define the various indices of performance as functions of ramp and shoulder-lane volume conditions for each type of ramp design considered.

5. Practical capacities were defined by obtaining solutions to the empirically derived models describing the

probability of delay in excess of 60 seconds. Ramp and shoulder-lane volume combinations that generated a probability of 0.15 constituted a practical capacity situation.

6. The average queue models were solved and percentile queue data were evaluated at practical capacity volume conditions to obtain ramp storage requirements for ramps operating at practical capacity.

7. The results obtained from the queuing and simulation analyses can be extremely useful in the design of new on-ramp facilities and in evaluating the adequacy of existing facilities. The procedure for applying these results to a particular ramp situation involves two steps:

   a. Obtain an estimate of the amount of traffic that is using, or is expected to use, the shoulder lane. This may be done by actual field study or by using Hess's lane-distribution models given in the chapter entitled "Descriptors of the Ramp Situation."

   b. Obtain possible capacity, practical capacity, and performance characteristics associated with practical capacity from the appropriate models derived in this study.

8. Monte Carlo simulation is a useful, practical, and efficient technique for studying freeway on-ramp operations. The proposed simulator required approxi-

mately two minutes for each combination of ramp and shoulder-lane volumes that was simulated. Although constant sample sizes of 1000 ramp vehicles were observed on each run, variations in the ramp flow-rates resulted in variation of the real time/computer time ratio. These ratios ranged from 360/1 to 30/1. Approximately one-half of the computer time was spent pre-loading the ramp system, preparing statistical summaries of the results, and writing the simulation report.

RECOMMENDATIONS FOR ADDITIONAL RESEARCH

Additional research in the simulation of on-ramp situations is recommended in two general areas:

1. Field studies should be conducted to evaluate and improve the proposed simulator. Specific micro-aspects that should be described more adequately are:
   a. ramp speeds,
   b. acceleration-deceleration characteristics, and
   c. gap-acceptance relationships.
2. Additional laboratory studies should be conducted with the simulator to:
   a. determine the affect of acceleration-lane length on ramp capacity, and
   b. evaluate the improvements in on-ramp operation that can be effected by metering the ramp traffic.

LIST OF REFERENCES

LIST OF REFERENCES

1. American Association of State Highway Officials, A Policy On The Geometric Design of Rural Highways, Washington: 1954

2. Committee on Highway Capacity, Highway Capacity Manual, U. S. Dept. of Commerce, Bureau of Public Roads, Washington: 1950.

3. Gerlough, D. L., "Traffic Inputs for Simulation on a Digital Computer," Proceedings, Highway Research Board, Vol. 38, Washington: 1959, pp. 480-492.

4. Hess, Joseph W., "Capacities and Characteristics of Ramp-Freeway Connections," Highway Research Board, Record No. 27, Washington: 1963, pp. 69-115.

5. IBM 7090/7094 Programming System, Reference Manual C28-6274-1, International Business Machine Corporation, White Plains, New York, 1963.

6. Kell, J. H., "A Theory of Traffic Flow on Urban Streets," Proceedings, The 13th Annual Western Section Meeting of the Institute of Traffic Engineers, San Francisco, California, 1960, pp. 66-70.

7. Levy, S. L., Aaron Glickstein, and Leon D. Findley, "A Study of the Application of Computer Simulation Techniques to Interchange Design Problems," Final Report, Midwest Research Institute, Missouri, 1960.

8. Levy, Sheldon L., and Philip A. Perchonok, "Application of Digital Simulation Techniques to Freeway On-Ramp Traffic Operations," Proceedings, Highway Research Board, Vol. 39, Washington: 1960, pp. 506-523.

9. Levy, Sheldon L., and Aaron Glickstein, "Application of Digital Simulation Techniques to Highway Design Problems," Paper presented at the Western Joint Computer Conference, Los Angeles, California, 1961.

10. Levy, Sheldon L., and Philip A. Perchonok, "Ramp Simulation Techniques on a Digital Computer," Highway Research Board, Bulletin No. 293, Washington: 1961.

11. Matson, T. M., W. S. Smith, and F. W. Hurd, Traffic Engineering, McGraw-Hill Book Companry, New York, 1955.

12. May, D., Jr., "Traffic Characteristics and Phenomena on High Density Controlled Access Facilities." Traffic Engineering 31: 1-19, 56 March 1961.

13. Moskowitz, Karl and Leonard Newman, "Notes on Freeway Capacity," Highway Research Board, Record No. 27, Washington: 1963, pp. 44-68.

14. Moskowitz, Karl "Research on Operating Characteristics of Freeways," Proceedings, Institute of Traffic Engineers, pp. 85-110, 1956.

15. Oliver, Robert M. Farnsworth Bisbee, Gerold Pestalozzi, and Jean-Claude Dysli, "Vehicles Queues in Mixed Traffic Streams," Progress Report, Institute of Transportation and Traffic Engineering, Report No. 35, California: 1962.

16. Pearson, R. H., and M. G. Ferreri, "Operational Study--Schuylkill Expressway," Highway Research Board, Bulletin No. 293, Washington: 1961, pp. 104-123.

17. Schuhl, A., "The Probability Theory Applied to Distribution of Vehicles on Two-Lane Highways," Poisson and Traffic, Eno Foundation for Highway Traffic Control, Saugatuck, Conn., 1955, pp. 59-75.

18. Weiss, G. M., and A. A. Maradudin, "Some Problems in Traffic Delay," Operations Research, Vol. 10, No. 1, Baltimore: 1962, pp. 74-141.

19. Wohl, Martin, "Simulation--Its Application to Traffic Engineering, Part I," Traffic Engineering, Vol. 30, No. 11, August, 1960, pp. 13-17, 29.

20. Wohl, M. "Simulation--Its Application to Traffic Engineering, Part II," Traffic Engineering, Vol. 31, No. 11, pp. 19-25, 56, October, 1960.

General References

1. Adams, W. F., "Road Traffic Considered as a Random Series," Journal of the Institution of Civil Engineers, Vol. 4, November, 1936, pp. 121-130.

2. Bissell, H. H., "Traffic Gap Acceptance from a Stop Sign," Graduate Research Report (unpublished), Institute of Transportation and Traffic Engineering, University of California, Berkeley, 1960.

3. Cox, D. R., and W. L. Smith, Queues, John Wiley and Sons, Inc., New York, 1961.

4. Garwood, F., "An Application of the Theory of Probability to the Operations of Vehicular-Controlled Traffic Signal," Journal, Royal Statistical Society, Sup. VII (1940).

5. Gerlough, D. L., "Use of Poisson Distribution in Highway Traffic," Poisson and Traffic, Eno Foundation for Highway Traffic Control, Saugatuck, Conn., 1955, pp. 1-58.

6. Gerlough, D. L., "Simulation of Freeway Traffic by an Electronic Computer," Proceedings, Highway Research Board, Vol. 35, Washington: 1956, pp. 543-547.

7. Greenshields, B. D. and F. M. Weida, Statistics with Application to Highway Traffic Analysis, Eno Foundation for Highway Traffic Control, Saugatuck, Conn., 1952.

8. Haight, Frank A., E. Farnsworth Bisbee and Charles Wojcik, "Some Mathematical Aspects of the Problem of Merging," Highway Research Board, Bulletin No. 357, Washington: 1962, pp. 1-14.

9. Herman, Robert and George Weiss, "Comments on the Highway Crossing Problem," Operations Research, Vol. 9, No. 6, Baltimore: 1960, pp. 828-840.

10. Kell, J. H., "Analyzing Vehicular Delay at Intersections through Simulation," Highway Research Board, Bulletin No. 357, Washington: 1962, pp. 28-39.

11. Lewis, R. M., "The Simulation of Traffic Flow to Obtain Volume Warrants For Intersection Control," Highway Research Board, Record No. 15, Washington: 1963, pp. 1-43.

12. McCracken, Daniel D., A Guide to Fortran Programming, John Wiley & Sons, Inc., New York: 1962.

13. Morse, P. M., Queues, Inventories, and Maintenance, John Wiley & Sons, Inc., New York: 1958.

14. Oliver, Robert M. and Leonard Newman, "Effect of Trucks on Freeway Flows," Highway Research Board, Record No. 15, Washington: 1963, pp. 67-72.

15. Oliver, R. M., and E. F. Bisbee, "Queuing For Gaps in High Flow Traffic Streams," Operations Research, Vol. 10, No. 2, 1962.

16. Oliver, R. M., E. F. Bisbee, and G. Pestalozzi, "Vehicle Space-Occupancy in Moving Streams of Traffic," Research Report No. 34, Institute of Transportation and Traffic Engineering, University of California, Berkeley: 1962.

17. Sasieni, M., A. Yaspna, and L. Friedman, Operations Research, John Wiley & Sons, Inc., New York: 1959.

18. Tanner, J. C., "The Delay to Pedestrians Crossing a Road," Biometrika, Vol. 38, Parts 3 and 4, December, 1951.

19. Wynn, F. H., et. al., "Studies of Weaving and Merging Traffic," Technical Bulletin 4, Yale University, Bureau of Highway Traffic, New Haven, Conn., 1948.

APPENDIX

APPENDIX A

Computer Programs for Determination of Possible Capacities of Freeway On-Ramps

(Fortran IV Coding for IBM 7090)

APPENDIX A.1

Program for Possible Capacity of Freeway On-Ramp

With No Acceleration Lane and Stop-Sign Control

```
$ID   3046*003*005*000**    RF DAWSON
$EXCUTE        IBJOB
$IBJOB
$IBFTC MAIN    NODECK
C      ANALYSIS OF POSSIBLE RAMP CAPACITIES.
C      NO ACCELERATION LANE -- STOP-SIGN CONTROL
C      A SHIFTED EXPONENTIAL HEADWAY MODEL IS USED TO
C      DESCRIBE THE DISTRIBUTION OF SHOULDER LANE VEHICLES.
C      MINIMUM HEADWAYS ARE DESCRIBED
C      BY THE MODEL--D=0.30+VOL/10000.
C      A CONTINUOUS BACKLOG OF VEHICLES
C      IS ASSUMED TO BE ON THE RAMP.
C      GAP ACCEPTANCE IS DESCRIBED BY THE MODEL--
C      PROB. OF ACPT. = (1.-EXP(-(T-3.3)/(6.5-3.3)))
       DIMENSION A(1001),B(1000),C(1000),D(1000),X(2),
      1RAMCAP(18),RCAP(18,20),VOL(18)
C      READ IN GAP LIMIT DATA
     1 READ(5,5) X(1),X(2),DT
     5 FORMAT(3F5.2)
    20 ALPHA = 1./(6.5-3.3)
C      A(I) = GAP TIME LIMITS
    21 DO 196 N=1,18,1
    22 A(1) = X(1)
    24 A(2) = X(2)
    25 DO 35 I=3,1001,1
    30 XI = I
    35 A(I) = A(2)+(XI-2.)*DT
    40 DO 43 I=1,1000,1
    41 B(I) = 0.
    42 C(I) = 0.
    43 D(I) = 0.
    50 SHLVOL = N*100
    53 DELTA = 0.30+SHLVOL/10000.
    55 BETA = 1./((3600./SHLVOL)-DELTA)
C      B(I)=AVERAGE LENGTH OF GAP INTERVAL
    60 DO 65 I=1, 1000,1
    65 B(I) = ((A(I+1)*EXP(-BETA*A(I+1))-A(I)*EXP(-BETA*
      1A(I)))/(EXP(-BETA*A(I+1))-EXP(-BETA*A(I))))+1./BETA
C      B(I)=PROBABILITY OF REJECTING GAP OF GIVEN LENGTH
    70 DO 75 I=1,1000,1
    75 B(I)=EXP(-ALPHA*B(I)-3.3)
C      C(I)=PROBABILITY OF ACCEPTING GAP OF GIVEN LENGTH
    80 DO 85 I=1, 1000,1
    85 C(I)=1.-B(I)
```

```
C      A(I) = PORTION OF GAPS IN GIVEN INTERVAL
   90 DO 95 I=1, 1000,1
   95 A(I)=EXP(-BETA*(A(I)-DELTA))-EXP(-BETA*(A(I+1)-DELTA))
C      RAMCAP=POSSIBLE RAMP CAPACITY
  100 RAMCAP(N) = 0.
C      D(I) = ACCUMULATED PROBABILITY OF I-VEHICLES
C      ENTERING FROM RAMP
  105 DO 170 I=1, 1000,1
  110 D(I)=A(I)
  115 DO 120 J=1, I, 1
  120 D(I)=D(I)*C(J)
  123 KI=I + 1
  125 DO 160 K = KI, 1000, 1
  130 E=A(K)
  133 LKI = K-I+1
  135 DO 140 L=LKI, K, 1
  140 E=E*C(L)
  143 IKI=K-I
  145 E=E*B(IKI)
  150 D(I)=D(I) + E
  155 IF(E-0.00000001)165, 160, 160
  160 CONTINUE
  165 IF(D(I)-0.00000001)175, 170, 170
  170 CONTINUE
C      D(J) = AMOUNT OF CAPACITY UTILIZED
C      BY QUEUES I-VEHICLES IN LENGTH
  175 DO 185 J=1, I, 1
  178 XJ=J
  180 D(J) = D(J)*XJ*SHLVOL
  185 RAMCAP(N) = RAMCAP(N)+D(J)
C      RCAP(N,J) = AMOUNT OF CAPACITY UTILIZED
C      BY QUEUES OF J OR LESS VEHICLES WITH
C      A SHOULDER LANE VOLUME OF N*100 VPH
  188 RCAP(N,1) = D(1)
  190 DO 195 J=2,20,1
  195 RCAP(N,J) = RCAP(N,J-1)+D(J)
  196 CONTINUE
  197 DO 198 N=1,18,1
  198 VOL(N) = N*100
  199 WRITE (6,200)
  200 FORMAT(1H1,43X,
     139HPOSSIBLE CAPACITIES OF FREEWAY ON-RAMPS)
  202 WRITE (6,204) (N,N=1,20)
  204 FORMAT(1H0,53X,17HSTOP SIGN CONTROL,//5X,
     12HSH,14X,40HAMOUNT OF CAPACITY UTILIZED BY QUEUES OF,
     21X,33HLENGTH EQUAL TO OR SHORTER THAN X,16X,5HPOSS.,/
     33X,6HVOLUME,35X,27HLENGTH OF QUEUE--X VEHICLES,41X,
     43HCAP,/,2X,5H(VPH),20I5,3X,5H(VPH),/)
```

```
  205 DO 210 N=1,18
  210 WRITE(6,215) VOL(N),(RCAP(N,J),J=1,20),RAMCAP(N)
  215 FORMAT(3X,F5.0,1X,(20F5.0),2X,F5.0)
  300 STOP
      END
7/8
 3.30 8.25 4.45
```

APPENDIX A.2

Program for Possible Capacity of Freeway On-Ramp With No Acceleration Lane and Yield-Sign Control

```
$ID   3046*003*005*000**     RF DAWSON
$EXECUTE        IBJOB
$IBJOB
$IBFTC MAIN     NODECK
C       ANALYSIS OF POSSIBLE RAMP CAPACITIES
C       NO ACCELERATION LANE -- YEILD-SIGN CONTROL
C       A SHIFTED EXPONENTIAL HEADWAY MODEL IS USED TO
C       DESCRIBE THE DISTRIBUTION OF SHOULDER LANE VEHICLES.
C       MINIMUM HEADWAYS ARE DESCRIBED
C       BY THE MODEL--D=0.30+VOL/10000.
C       A CONTINUOUS BACKLOG OF VEHICLES
C       IS ASSUMED TO BE ON THE RAMP.
C       GAP ACCEPTANCE IS DESCRIBED BY THE FOLLOWING MODELS--
C       LEAD VEHICLE - PR.ACPT.=(1.-EXP(-(T-3.3)/(6.5-3.3))
C       TRAIL VEHICLE - PR.ACPT.=(1.-EXP(-(T-2.0)/(5.0-2.0))
        DIMENSION A(1001),B(1000),C1(1000),C2(1000),D(1000),
       1X(2),RAMCAP(18),RCAP(18,20),VOL(18)
C       READ IN GAP LIMIT DATA
      1 READ(5,5) X(1),X(2),DT
      5 FORMAT(3F5.2)
     10 ALPHA1 = 1./(6.5-3.3)
     20 ALPHA2 = 1./(5.0-2.0)
C       A(I) = GAP TIME LIMITS
     21 DO 196 N=1,18,1
     22 A(1) = X(1)
     24 A(2) = X(2)
     25 DO 35 I=3,1001,1
     30 XI = I
     35 A(I) = A(2)+(XI-2.)*DT
     40 DO 43 I=1,1000,1
     41 B(I) = 0.
     42 C1(I) = 0.
        C2(I) = 0.
     43 D(I) = 0.
     50 SHLVOL = N*100
     53 DELTA = 0.30+SHLVOL/10000.
     55 BETA = 1./((3600./SHLVOL)-DELTA)
C       B(I)=AVERAGE LENGTH OF GAP INTERVAL
     60 DO 65 I=1, 1000,1
     65 B(I) = ((A(I+1)*EXP(-BETA*A(I+1))-A(I)*EXP(-BETA*
       1A(I)))/(EXP(-BETA*A(I+1))-EXP(-BETA*A(I))))+1./BETA
C       C1(I) = LEADING VEHICLE PROBABILITY OF ACCEPTING GAP
C       OF GIVEN LENGTH
```

```
   66 DO 67 I=1,1000,1
   67 C1(I) = 1.-EXP(-ALPHA1*B(I)-3.3)
C     B(I) = TRAILING VEHICLE PROBABILITY OF REJECTING
C     GAP OF GIVEN LENGTH
   70 Do 75 I=1,1000,1
   75 B(I) = EXP(-ALPHA2*B(I)- 2.0)
C     C2(I) = TRAILING VEHICLE PROBABILITY OF ACCEPTING
C     GAP OF GIVEN LENGTH
   80 DO 85 I=1,1000,1
   85 C2(I) = 1.-B(I)
C     A(I) = PORTION OF GAPS IN GIVEN INTERVAL
   90 DO 95 I=1, 1000,1
   95 A(I)=EXP(-BETA*(A(I)-DELTA))-EXP(-BETA*(A(I+1)-DELTA))
C     RAMCAP=POSSIBLE RAMP CAPACITY
  100 RAMCAP(N) = 0.
C     D(I) = ACCUMULATED PROBABILITY OF I-VEHICLES
C     ENTERING FROM RAMP
  105 DO 170 I=1, 1000,1
  110 D(I)=A(I)
  112 NONSTP = I-1
  115 DO 120 J=1,NONSTP,1
  120 D(I) = D(I)*C2(J)
  122 D(I) = D(I)*C1(I)
  123 KI=I + 1
  125 DO 160 K = KI, 1000,1
  130 E=A(K)
  133 LKI = K-I+1
  134 NONSTP = K-1
  135 DO 140 L=LKI,NONSTP,1
  140 E = E*C2(L)
  141 E = E*C1(K)
  143 IKI=K-I
  145 E=E*B(IKI)
  150 D(I)=D(I) + E
  155 IF(E-0.00000001)165, 160, 160
  160 CONTINUE
  165 IF(D(I)-0.00000001)175, 170, 170
  170 CONTINUE
C     D(J) = AMOUNT OF CAPACITY UTILIZED
C     BY QUEUES I-VEHICLES IN LENGTH
  175 DO 185 J=1, I, 1
  178 XJ=J
  180 D(J) = D(J)*XJ*SHLVOL
  185 RAMCAP(N) = RAMCAP(N)+D(J)
C     RCAP(N,J) = AMOUNT OF CAPACITY UTILIZED
C     BY QUEUES OF J OR LESS VEHICLES WITH
C     A SHOULDER LANE VOLUME OF N*100 VPH
```

```
  188 RCAP(N,1) = D(1)
  190 DO 195 J=2,20,1
  195 RCAP(N,J) = RCAP(N,J-1)+D(J)
  196 CONTINUE
  197 DO 198 N=1,18,1
  198 VOL(N) = N*100
  199 WRITE (6,200)
  200 FORMAT(1H1,43X,
     139HPOSSIBLE CAPACITIES OF FREEWAY ON-RAMPS)
  202 WRITE (6,204) (N,N=1,20)
  204 FORMAT(1HO,53X,18HYIELD SIGN CONTROL,//5X,
     12HSH,14X,40HAMOUNT OF CAPACITY UTILIZED BY QUEUES OF,
     21X,33HLENGTH EQUAL TO OR SHORTER THAN X,16X,5HPOSS.,/
     33X,6HVOLUME,35X,27HLENGTH OF QUEUE--X VEHICLES,41X,
     43HCAP,/,2X,5H(VPH),20I5,3X,5H(VPH),/)
  205 DO 210 N=1,18
  210 WRITE(6,215) VOL(N),(RCAP(N,J),J=1,20),RAMCAP(N)
  215 FORMAT(3X,F5.0,1X,(20F5.0),2X,F5.0)
  300 STOP
      END
7/8
 3.30 5.80 2.00
```

APPENDIX A.3

Program for Possible Capacity of Freeway On-Ramp

With an Acceleration Lane and No Sign Control

```
$ID   3046*003*005*000**     RF DAWSON
$EXECUTE        IBJOB
$IBJOB
$IBFTC MAIN     NODECK
C      ANALYSIS OF POSSIBLE RAMP CAPACITIES.
C      ACCELERATION LANE -- NO SIGN CONTROL
C      A SHIFTED EXPONENTIAL HEADWAY MODEL IS USED TO
C      DESCRIBE THE DISTRIBUTION OF SHOULDER LANE VEHICLES.
C      MINIMUM HEADWAYS ARE DESCRIBED
C      BY THE MODEL--D=0.30+VOL/10000.
C      A CONTINUOUS BACKLOG OF VEHICLES
C      IS ASSUMED TO BE ON THE RAMP.
C      GAP ACCEPTANCE IS DESCRIBED BY THE FOLLOWING MODELS--
C      LEADING VEHICLE - PR.ACPT. = 0.859*LN(T)-0.787
C      TRAILING VEHICLES - PR.ACPT. = 0.721*LN(T)
       DIMENSION A(1001),B(1000),C1(1000),C2(1000),D(1000),
      1X(2),RAMCAP(18),RCAP(18,20),VOL(18)
C      READ IN GAP LIMIT DATA
     1 READ(5,5) X(1),X(2),DT
     5 FORMAT(3F5.2)
C      A(I) = GAP TIME LIMITS
    20 DO 196 N=1,18,1
    22 A(1) = X(1)
    24 A(2) = X(2)
    25 DO 35 I=3,1001,1
    30 XI = I
    35 A(I) = A(2)+(XI-2.)*DT
    40 DO 43 I=1,1000,1
    41 B(I) = 0.
    42 C1(I) = 0.
       C2(I) = 0.
    43 D(I) = 0.
    50 SHLVOL = N*100
    53 DELTA = 0.30+SHLVOL/10000.
    55 BETA = 1./((3600./SHLVOL)-DELTA)
C      B(I)=AVERAGE LENGTH OF GAP INTERVAL
    60 DO 65 I=1, 1000,1
    65 B(I) = ((A(I+1)*EXP(-BETA*A(I+1))-A(I)*EXP(-BETA*
      1A(I)))/(EXP(-BETA*A(I+1))-EXP(-BETA*A(I))))+1./BETA
C      C1(I) = LEADING VEHICLE PROBABILITY OF ACCEPTING
C      GAP OF GIVEN LENGTH
    68 A1 = 1.00/ALOG(4.0)
    70 DO 86 I=1,1000,1
```

```
   72 IF(B(I)-4.00)74,84,84
   74 IF(B(I)-1.00)76,80,80
   76 C1(I) = 0.0
   78 GO TO 86
   80 C1(I) = A1*ALOG(B(I))
   82 GO TO 86
   84 C1(I) = 1.0
   86 CONTINUE
C     C2(I) = TRAILING VEHICLE PROBABILITY OF ACCEPTING
C     GAP OF GIVEN LENGTH
  267 A2 = ALOG(2.5)
  268 A1 = 1.00/(ALOG(8.0)-A2)
  269 A3 = A1*A2
  270 DO 286 I=1,1000,1
  272 IF(B(I)-8.00)274,284,284
  274 IF(B(I)-2.50)276,280,280
  276 C2(I) = 0.0
  278 GO TO 286
  280 C2(I) = A2*ALOG(B(I))-A3
  282 GO TO 286
  284 C2(I) = 1.00
  286 CONTINUE
C     B(I) = PROBABILITY OF REJECTING GAP OF GIVEN LENGTH
   88 DO 89 I=1,1000,1
   89 B(I) = 1.0-C2(I)
C     A(I) = PORTION OF GAPS IN GIVEN INTERVAL
   90 DO 95 I=1, 1000, 1
   95 A(I)=EXP(-BETA*(A(I)-DELTA))-EXP(-BETA*(A(I+1)-DELTA))
C     RAMCAP=POSSIBLE RAMP CAPACITY
  100 RAMCAP(N) = 0.
C     D(I) = ACCUMULATED PROBABILITY OF I-VEHICLES
C     ENTERING FROM RAMP
  105 DO 170 I=1, 1000, 1
  110 D(I)=A(I)
  112 NONSTP = I-1
  115 DO 120 J=1,NONSTP,1
  120 D(I) = D(I)*C2(J)
  122 D(I) = D(I)*C1(I)
  123 KI=I + 1
  125 DO 160 K = KI, 1000, 1
  130 E=A(K)
  133 LKI = K-I+1
  134 NONSTP = K-1
  135 DO 140 L=LKI, NONSTP,1
  140 E = E*C2(L)
  141 E = E*C1(K)
  143 IKI=K-I
  145 E=E*B(IKI)
  150 D(I)=D(I) + E
```

```
  155 IF(E-0.00000001)165, 160, 160
  160 CONTINUE
  165 IF(D(I)-0.00000001)175, 170, 170
  170 CONTINUE
C     D(J) = AMOUNT OF CAPACITY UTILIZED
C     BY QUEUES I-VEHICLES IN LENGTH
  175 DO 185 J=1, I, 1
  178 XJ=J
  180 D(J) = D(J)*XJ*SHLVOL
  185 RAMCAP(N) = RAMCAP(N)+D(J)
C     RCAP(N,J) = AMOUNT OF CAPACITY UTILIZED
C     BY QUEUES OF J OR LESS VEHICLES WITH
C     A SHOULDER LANE VOLUME OF N*100 VPH
  188 RCAP(N,1) = D(1)
  190 DO 195 J=2,20,1
  195 RCAP(N,J) = RCAP(N,J-1)+D(J)
  196 CONTINUE
  197 DO 198 N=1, 18, 1
  198 VOL(N) = N*100
  199 WRITE (6,200)
  200 FORMAT(1H1,43X,
     139HPOSSIBLE CAPACITIES OF FREEWAY ON-RAMPS)
  202 WRITE (6,204) (N,N=1,20)
  204 FORMAT(1H0,47X,29HACCELERATION LANE--NO CONTROL,//5X,
     12HSH,14X,40HAMOUNT OF CAPACITY UTILIZED BY QUEUES OF,
     21X,33HLENGTH EQUAL TO OR SHORTER THAN X,16X,5HPOSS.,/
     33X,6HVOLUME,35X,27HLENGTH OF QUEUE--X VEHICLES,41X,
     43HCAP,/,2X,5H(VPH),20I5,3X,5H(VPH),/)
  205 DO 210 N=1,18
  210 WRITE(6,215) VOL(N),(RCAP(N,J),J=1,20),RAMCAP(N)
  215 FORMAT(3X,F5.0,1X,(20F5.0),2X,F5.0)
  300 STOP
      END
7/8
 2.50 4.80 1.80
```

APPENDIX B

Computer Programs For Simulation of Freeway On-Ramps

(Fortran IV and Map Coding for IBM 7090)

APPENDIX B.1

Program for Simulation of Freeway On-Ramp

With No Acceleration Lane and Stop-Sign Control

```
$ID   3046*012*105*000**         RF DAWSON
$EXECUTE       IBJOB
$IBJOB
$IBFTC MAIN
C
C      RAMP CAPACITY BY DIGITAL SIMULATION
C
C      NO ACCELERATION LANE -- STOP SIGN CONTROL
C
C      DEFINITIONS
C
C      ACCEPT      = NAME OF SUBROUTINE TO DETERMINE IF GAP
C                    IS ACCEPTABLE
C      ACCL        = ACCELERATION RATE
C      ACLDST      = DISTANCE TRAVELED DURING ACCELERATION
C                    FROM RAMP SPEED TO SHOULDER LANE SPEED
C      ACLTIM      = TIME FOR ACCELERATION FROM RAMP SPEED TO
C                    SHOULDER LANE SPEED
C      ACPTNO      = NUMBER RETURNED BY ACCEPT.  IF ACPTNO IS
C                    MINUS OR ZERO, GAP IS ACCEPTABLE.  IF
C                    ACPTNO IS POSITIVE, GAP IS NOT ACCEPTABLE.
C      ARAND       = NAME OF SUBROUTINE THAT GENERATES RANDOM
C                    NUMBERS TO SAMPLE GAP ACCEPTANCE
C                    DISTRIBUTION
C      ARDNO       = RANDOM NUMBER GENERATED BY ARAND
C      ASG         = AVAILABLE SHOULDER LANE GAP
C      ASRTIM      = ACCUMULATED SERVICE TIMES OF ALL VEHICLES
C      ASRTM1      = ACCUMULATED SERVICE TIMES OF VEHICLES THAT
C                    DO NOT WAIT FOR QUEUE
C      ASRTM2      = ACCUMULATED SERVICE TIMES OF VEHICLES
C                    THAT WAIT FOR QUEUE
C      ASSRT1      = ACCUMULATED SQUARES OF SERVICE TIMES OF
C                    VEHICLES THAT DO NOT WAIT FOR QUEUE
C      ASSRT2      = ACCUMULATED SQUARES OF SERVICE TIMES OF
C                    VEHICLES THAT WAIT FOR QUEUE
C      ASSRTM      = ACCUMULATED SQUARES OF SERVICE TIMES OF
C                    ALL VEHICLES
C      ASSWT2      = ACCUMULATED SQUARES OF WAIT TIMES OF
C                    VEHICLES THAT WAIT FOR QUEUE
C      ASSYT1      = ACCUMULATED SQUARES OF SYSTEM TIMES OF
C                    VEHICLES THAT DO NOT WAIT FOR QUEUE
C      ASSYT2      = ACCUMULATED SQUARES OF SYSTEM TIMES OF
C                    VEHICLES THAT WAIT FOR QUEUE
```

```
C     ASSYTM    = ACCUMULATED SQUARES OF SYSTEM TIMES OF
C                 ALL VEHICLES
C     ASWAIT    = ACCUMULATED SQUARES OF WAIT TIMES OF ALL
C                 VEHICLES
C     ASWT2     = ACCUMULATED SQUARES OF SERVICE TIMES
C                 OF VEHICLES THAT WAIT
C     ASYTM1    = ACCUMULATED SYSTEM TIMES OF VEHICLES THAT
C                 DO NOT WAIT FOR QUEUE
C     ASYTM2    = ACCUMULATED SYSTEM TIME OF VEHICLES THAT
C                 WAIT FOR QUEUE
C     ASYTM     = ACCUMULATED SYSTEM TIMES OF ALL VEHICLES
C     AVQL      = AVERAGE QUEUE LENGTH
C     AVSRT1    = AVERAGE SERVICE TIME OF VEHICLES THAT DO
C                 NOT WAIT FOR QUEUE
C     AVSRT2    = AVERAGE SERVICE TIME OF VEHICLES THAT WAIT
C                 FOR QUEUE
C     AVSRTM    = AVERAGE SERVICE TIME OF ALL VEHICLES
C     AVSYT1    = AVERAGE SYSTEM TIME OF VEHICLES THAT DO
C                 NOT WAIT FOR QUEUE
C     AVSYT2    = AVERAGE SYSTEM TIME OF VEHICLES THAT
C                 WAIT FOR QUEUE
C     AVSYTM    = AVERAGE SYSTEM TIME OF ALL VEHICLES
C     AVWAIT    = AVERAGE WAIT OF ALL VEHICLES
C     AVWT1     = AVERAGE WAIT OF VEHICLES THAT DO NOT WAIT
C                 FOR QUEUE
C     AVWT2     = AVERAGE WAIT OF VEHICLES THAT WAIT FOR
C                 QUEUE
C     AWAIT2    = ACCUMULATED WAIT TIMES OF VEHICLES THAT
C                 WAIT FOR QUEUE
C     AWAIT     = ACCUMULATED WAIT TIMES OF ALL VEHICLES
C     BEGTIM    = TIME FOR VEHICLE TO MOVE FROM STOP LINE
C                 TO POINT OF ENTRY INTO SHOULDER LANE
C     CLEAR     = TIME FOR FIRST-IN-LINE VEHICLE TO CLEAR
C                 FIRST-IN-LINE POSITION
C     D         = MINIMUM HEADWAY IN SHOULDER LANE STREAM
C     DCLDST    = DISTANCE TRAVELED DURING DECELERATION FROM
C                 RAMP SPEED TO STOP
C     DCLTIM    = TIME TO DECELERATE FROM RAMP SPEED TO STOP
C     DECL      = DECELERATION RATE
C     DELAY     = DIFFERENCE BETWEEN ACTUAL TRAVEL TIME AND
C                 TRAVEL TIME THROUGH AN EMPTY SYSTEM
C     DUMMY     = A DUMMY VARIABLE USED TO SATISFY FORTRAN
C                 IV RULES FOR CALLING SUBROUTINES
C     HOP       = TIME FOR SECOND-IN-LINE VEHICLE TO MOVE
C                 UP TO FIRST-IN-LINE POSITION
C     I         = INDEX OF VEHICLE GENERATED
C     IC        = INDEX OF QUEUE CONDITION
C                 1 - NO QUEUE
C                 2 - QUEUE
```

```
C      J            = INDEX FOR VEHICLES NOT WAITING FOR QUEUE
C      K            = INDEX FOR VEHICLES WAITING FOR QUEUE
C      L            = INDEX FOR OBSERVED VEHICLES
C      LAG          = INDEX FOR TYPE OF SHOULDER LANE OPENING
C                     0 - GAP ACCEPTED
C                     1 - LAG ACCEPTED
C      LQ(L)        = QUEUE EXISTING AS L-TH VEHICLE ENTERS
C                     SYSTEM
C      LQMAX        = MAXIMUM QUEUE OBSERVED
C      NOSIMS       = NUMBER OF SIMULATION RUN
C      NRDEPT       = NUMBER OF RAMP VEHICLE DEPARTURES
C      NSVEH        = NUMBER OF SHOULDER LANE VEHICLES GENERATED
C                     PAST RAMP ENTRANCE
C      NVW          = NUMBER OF VEHICLES THAT WAIT FOR A QUEUE
C      NVW**        = NUMBER OF VEHICLES WAITING LONGER THAN **
C                     SECONDS WHERE ** HAS VALUES OF 30, 60,
C                     90, 120, 150, AND 180
C      NVWGT        = NAME OF SUBROUTINE TO DETERMINE NUMBER OF
C                     VEHICLES BY LENGTH OF DELAY
C      PAG          = PROBABILITY OF ACCEPTING GAP
C      PIEV         = TIME FOR PERCEPTION, INTELLECTION, AND
C                     VOLITION AS INFLUENCED BY EMOTIONAL STATE
C      PVW***       = PERCENT OF VEHICLES DELAYED LONGER THAN
C                     *** SECONDS WHERE *** HAS VALUES OF 30, 60,
C                     90, 120, 150, AND 180
C      P85          = 85-TH PERCENTILE QUEUE LENGTH
C      P90          = 90-TH PERCENTILE QUEUE LENGTH
C      P95          = 95-TH PERCENTILE QUEUE LENGTH
C      RAMP HEADWAY DISTRIBUTION CONSTANTS
C                     RA1 = PORTION UNDER RESTRICTED CONDITION
C                     RT1 = MEAN RESTRICTED HEADWAY
C                     RD1 = MINIMUM RESTRICTED HEADWAY
C                     RA2 = PORTION UNDER FREE CONDITION
C                     RT2 = MEAN FREE HEADWAY
C                     RD2 = MINIMUM FREE HEADWAY
C      RAMP         = NAME OF SUBROUTINE THAT RETURNS RAMP
C                     HEADWAYS
C      RAMVOL       = RAMP VOLUME CALLED FOR ON DATA CARD
C      RAMVPH       = RAMP VOLUME GENERATED
C      RAT(I)       = RAMP ARRIVAL TIME OF I-TH VEHICLE
C      RATFQ(I)     = TIME OF ARRIVAL OF I-TH VEHICLE AT THE
C                     FIRST-IN-LINE POSITION
C      RDT(I)       = TIME OF DEPARTURE OF THE I-TH VEHICLE
C                     FROM THE SYSTEM
C      RELTIM(I)    = TIME OF RELEASE OF I-TH VEHICLE FROM THE
C                     FIRST-IN-LINE POSITION
```

```
C       RH            = RAMP HEADWAY GENERATED BY RAMP SUBROUTINE
C       RPDATA        = NAME OF SUBROUTINE THAT RETURNS RA1, RT1,
C                       RD1, RA2, RT2, AND RD2
C       RRAND*        = NAMES OF SUBROUTINES THAT RETURN RANDOM
C                       NUMBERS TO SAMPLE HEADWAY DISTRIBUTIONS.
C                       SINCE THERE ARE FIVE SUCH DISTRIBUTIONS
C                       * TAKES ON VALUES OF 1, 2, 3, 4, AND 5
C       RRDNO1        = A RANDOM NUMBER RETURNED BY RRAND* TO BE
C                       USED TO SELECT EITHER THE RESTRICTED OR
C                       THE FREE PORTION OF THE RAMP HEADWAY
C                       DISTRIBUTION
C       RRDNO2        = A RANDOM NUMBER RETURNED BY RRAND* TO BE
C                       USED TO SAMPLE EITHER THE RESTRICTED OR
C                       THE FREE PORTION OF THE RAMP HEADWAY
C                       DISTRIBUTION AS DEFINED BY RRDNO1
C       RSPD          = RAMP SPEED
C       SAT1          = ARRIVAL TIME OF LAST SHOULDER LANE VEHICLE
C       SAT2          = ARRIVAL TIME OF NEXT SHOULDER LANE VEHICLE
C       SDSRT1        = STD. DEV. OF SERVICE TIMES OF VEHICLES
C                       THAT DO NOT WAIT FOR A QUEUE
C       SDSRT2        = STD. DEV. OF SERVICE TIMES OF VEHICLES
C                       THAT WAIT FOR A QUEUE
C       SDSRTM        = STD. DEV. OF SERVICE TIMES OF ALL OBSERVED
C                       VEHICLES
C       SDWAIT        = STD. DEV. OF WAIT TIMES OF ALL OBSERVED
C                       VEHICLES
C       SDWT1         = STD. DEV. OF WAIT TIMES OF VEHICLES THAT
C                       DO NOT WAIT FOR A QUEUE
C       SDWT2         = STD. DEV. OF WAIT TIMES OF VEHICLES THAT
C                       WAIT FOR A QUEUE
C       SDSYT1        = STD. DEV. OF SYSTEM TIMES OF VEHICLES
C                       THAT DO NOT WAIT FOR A QUEUE
C       SDSYT2        = STD. DEV. OF SYSTEM TIMES OF VEHICLES
C                       THAT WAIT FOR A QUEUE
C       SDSYTM        = STD. DEV. OF SYSTEM TIMES OF ALL OBSERVED
C                       VEHICLES
C       SERVICE TIME = TIME ON RAMP AS FIRST-IN-LINE VEHICLE
C                       WAITING FOR ACCEPTABLE GAP
C       SFGT          = TIME AT WHICH RAMP VEHICLE CAN GET TO
C                       ENTRY POINT AND FROM WHICH NEXT SHOULDER
C                       LANE ARRIVAL IS SCALED TO DETERMINE
C                       AVAILABLE SHOULDER LANE GAP
C       SH            = SHOULDER-LANE HEADWAYS RETURNED BY
C                       SHLANE
C       SHDATA        = NAME OF SUBROUTINE THAT RETURNS THE D AND
C                       Z PARAMETERS OF THE SHOULDER LANE HEADWAY
C                       DISTRIBUTION
```

```
C       SHLANE     = NAME OF SUBROUTINE THAT RETURNS
C                    SHOULDER LANE HEADWAYS
C       SHLVOL     = SHOULDER LANE VOLUME CALLED FOR
C       SHLVPH     = SHOULDER LANE VOLUME GENERATED
C       SORT1      = NAME OF SUBROUTINE THAT PERFORMS A PUSH-
C                    DOWN SORT ON FLOATING-POINT QUANTITIES
C       SORT2      = NAME OF SUBROUTINE THAT PERFORMS A PUSH-
C                    DOWN SORT ON FIXED-POINT QUANTITIES
C       SRAND*     = NAMES OF SUBROUTINES THAT RETURN RANDOM
C                    NUMBERS TO SAMPLE SHOULDER LANE HEADWAY
C                    DISTRIBUTIONS.  SINCE THERE ARE FIVE SUCH
C                    DISTRIBUTIONS, * TAKES A VALUE OF 1, 2,
C                    3, 4, AND 5
C       SRDNO      = RANDOM NUMBER RETURNED BY THE SUBROUTINE
C                    SRAND*
C       SRTIM(L)   = SERVICE TIME OF THE L-TH OBSERVED VEHICLE
C       SRTIM1(J)  = SERVICE TIME OF THE J-TH VEHICLE THAT
C                    DOES NOT WAIT FOR A QUEUE
C       SRTIM2(K)  = SERVICE TIME OF THE K-TH VEHICLE THAT
C                    WAITS FOR A QUEUE
C       SSPD       = SHOULDER LANE SPEED
C       START      = DISTANCE FROM STOP LINE TO POINT OF ENTRY
C                    INTO SHOULDER LANE
C       SYSTIM(L)  = SYSTEM TIME OF THE L-TH OBSERVED VEHICLE
C       SYSTM1(J)  = SYSTEM TIME OF THE J-TH VEHICLE THAT DOES
C                    NOT WAIT FOR A QUEUE
C       SYSTM2(K)  = SYSTEM TIME OF THE K-TH VEHICLE THAT
C                    WAITS FOR A QUEUE
C       SYSTM      = TOTAL TIME A VEHICLE LOSES IN THE SYSTEM
C       TIME       = NAME OF VARIABLE USED AS CLOCK
C       TIMMAX     = MAXIMUM TIME SIMULATOR CAN RUN
C       TIM1       = TIME LOSS DURING DECELERATION
C       TIM2       = TIME LOSS DURING ACCELERATION
C       TMLOSS     = TIM1 + TIM2
C       TOTLOS     = TOTAL  TIME LOSS FOUND BY ADDING TMLOSS +
C                    SYSTEM TIME
C       TRWAIT(I)  = TIME AT WHICH 1-ST IN LINE POSITION
C                    BECOMES AVAILABLE FOR OCCUPANCY BY I-TH
C                    VEHICLE
C       T1         = ACCELERATION TIME DURING MOVEMENT FROM
C                    2ND TO 1ST-IN-LINE POSITION
C       T2         = DECELERATION TIME.DURING MOVEMENT FROM
C                    2ND TO 1ST-IN-LINE POSITION
C       VEHLTH     = VEHICLE LENGTH
C       VRSRT1     = VARIANCE OF SERVICE TIMES OF VEHICLES
C                    THAT DO NOT WAIT FOR A QUEUE
```

```
C       VRSRT2      = VARIANCE OF SERVICE TIMES OF VEHICLES
C                     THAT WAIT FOR A QUEUE
C       VRSRT       = VARIANCE OF SERVICE TIMES OF ALL OBSERVED
C                     VEHICLES
C       VRSYT1      = VARIANCE OF SYSTEM TIMES OF VEHICLES THAT
C                     DO NOT WAIT FOR A QUEUE
C       VRSYT2      = VARIANCE OF SYSTEM TIMES OF VEHICLES
C                     THAT WAIT FOR A QUEUE
C       VRSYT       = VARIANCE OF SYSTEM TIMES OF ALL OBSERVED
C                     VEHICLES
C       VRWAIT      = VARIANCE OF WAIT TIMES OF ALL OBSERVED
C                     VEHICLES
C       VRWT1       = VARIANCE OF WAIT TIMES OF VEHICLES THAT
C                     DO NOT WAIT FOR A QUEUE
C       VRWT2       = VARIANCE OF WAIT TIMES OF VEHICLES THAT
C                     WAIT FOR A QUEUE
C       W           = FLOATING POINT CONVERSION OF OBSERVED
C                     QUEUE LENGTH
C       WAIT TIME   = TIME ON RAMP WHILE IN THE N,N-1,. . ,4,3,
C                     AND 2 POSITIONS IN A QUEUE
C       WAIT2(K)    = WAIT TIME OF THE K-TH VEHICLE THAT WAITS
C                     FOR A QUEUE
C       WAIT(L)     = WAIT TIME OF THE L-TH OBSERVED VEHICLE
C       WQL         = SUM OF OBSERVED QUEUE LENGTHS
C       XI          = FLOATING POINT CONVERSION OF NUMBER OF
C                     VEHICLES OBSERVED
C       XJ          = FLOATING POINT CONVERSION OF TOTAL NUMBER
C                     OF VEHICLES THAT DO NOT WAIT FOR A QUEUE
C       XK          = FLOATING POINT CONVERSION OF TOTAL NUMBER
C                     OF VEHICLES THAT WAIT FOR A QUEUE
C       XNRDEP      = FLOATING POINT CONVERSION OF NUMBER OF
C                     RAMP VEHICLE DEPARTURES
C       XNSVEH      = FLOATING POINT CONVERSION OF NUMBER OF
C                     SHOULDER-LANE VEHICLES GENERATED PAST
C                     THE RAMP
C       XVW**       = FLOATING POINT CONVERSION OF NUMBER OF
C                     VEHICLES DELAYED LONGER THAN ** SECONDS
C                     WHERE ** TAKES ON VALUES OF 30,60,90,120,
C                     150, AND 180.
C       Z           = NEGATIVE OF DIFFERENCE BETWEEN MEAN AND
C                     MINIMUM SHOULDER LANE HEADWAYS
```

```
C     DIMENSION STORAGE
      DIMENSION RAT(1300),TRWAIT(1300),BATFQ(1300),
     1RDT(1300),WAIT2(1000),WAIT(1000),SRTIM1(1000),
     2SRTIM(1000),SYSTM1(1000),SYSTM2(1000),SYSTIM(1000),
     3RELTIM(1300),SRTIM2(1000),LQ(1000)
C     BEGIN SIMULATION RUN
      DO 500 NOSIMS=1,5,1
    4 WRITE (6,5) NOSIMS
    5 FORMAT(1H1,14X,9HNOSIMS = ,I1)
C     INPUT DATA FOR SIMULATION RUN
      READ(5,1)SHLVOL, RAMVOL
    1 FORMAT(F5.0, F6.0)
    6 WRITE (6,7) SHLVOL,RAMVOL
    7 FORMAT(15X,9HSHLVOL = ,F5.0,5X,9HRAMVOL = ,F5.0)
C     INITIALIZE STORAGE
    3 I=0
      L=0
      SAT1 = 0.
      SAT2=0.
      WQL=0.
      J=0
      K=0
      NRDEPT=0
      NSVEH=0
      NVW30=0
      NVW60=0
      NVW90=0
      NVW120=0
      NVW150=0
      NVW180=0
      ASRTM1=0.
      ASSRT1=0.
      AWAIT2=0.
      ASWT2=0.
      ASRTM2=0.
      ASSRT2=0.
      ASYTM1 = 0.
      ASSYT1 = 0.
      ASYTM2=0.
      ASSYT2=0.
      AWAIT=0.
      ASWAIT=0.
      ASRTIM=0.
      ASSRTM=0.
      ASYTM=0.
      ASSYTM=0.
```

```
C     CALCULATION OF PROGRAM CONSTANTS

      RSPD = 44.0
      SSPD = (1.47)*(52.0-0.008*SHLVOL)
      ACCL = 7.5
      DECL = 9.0
      VEHLTH = 21.5
      PIEV = 1.5
      START = 92.4
      T1 = SQRT(2.*VEHLTH/(ACCL+((ACCL/DECL)**2.)*DECL))
      T2 = (ACCL/DECL)*T1
      HOP = T1+T2
      CLEAR = SQRT(2.*VEHLTH/ACCL)
      BEGTIM = SQRT(2.*START/ACCL)
 1000 ACLTIM = (SSPD-RSPD)/ACCL
 1001 ACLDST = ((SSPD**2.)-(RSPD**2.))/(2.*ACCL)
 1002 DCLTIM = RSPD/DECL
 1003 DCLDST = (0.5*(RSPD**2.))/DECL
 1004 IF(ACLDST-DCLDST)1005,1010,1015
 1005 TIM1 = DCLTIM-ACLTIM-(DCLDST-ACLDST)/SSPD
 1007 GO TO 1020
 1010 TIM1 = DCLTIM-ACLTIM
 1012 GO TO 1020
 1015 TIM1 = DCLTIM-ACLTIM+(ACLDST-DCLDST)/SSPD
 1020 TIM2 = (SSPD/ACCL)-CLEAR
 1025 TMLOSS = TIM1+TIM2
    8 TIMMAX = 2.*(1300./RAMVOL)
      CALL RPDATA (RAMVOL, RA1, RT1, RD1, RA2, RT2, RD2)
      CALL SHDATA(SHLVOL, D, Z)

C     OUTPUT CONSTANTS OF RAMP AND SHOULDER LANE HEADWAY
C     DISTRIBUTIONS

    9 WRITE(6,10) RAMVOL,RA1,RT1,RD1,RA2,RT2,RD2,SHLVOL,D,Z
   10 FORMAT(15X,9HRAMVOL = ,F5.0,5X,
     16HRA1 = ,F5.3,5X,6HRT1 = F6.3,5X,6HRD1 = ,F5.2/
     234X6HRA2 = ,F5.3,5X,6HRT2 = ,F6.3,5X,6HRD2 = ,F5.2/
     315X,9HSHLVOL = ,F5.0,5X,4HD = ,F4.2,8X,4HZ = ,F5.2)
```

```
C     ROUTINE TO GENERATE FLOW OF 300 PRELIMINARY VEHICLES
C     THUS LOADING THE SIMULATOR BEFORE VEHICLES FOR
C     OBSERVATION ARE GENERATED
C
C     INCREMENT TOTAL VEHICLE COUNTER
  800 I = I + 1
C     CALL IN 2 RANDOM NUMBERS TO SAMPLE RAMP HEADWAY DIST.
  810 GO TO (812,814,816,818,820),NOSIMS
  812 RRDNO1 = RRAND1(DUMMY)
  813 RRDNO2 = RRAND1(DUMMY)
      GO TO 822
  814 RRDNO1 = RRAND2(DUMMY)
  815 RRDNO2 = RRAND2(DUMMY)
      GO TO 822
  816 RRDNO1 = RRAND3(DUMMY)
  817 RRDNO2 = RRAND3(DUMMY)
      GO TO 822
  818 RRDNO1 = RRAND4(DUMMY)
  819 RRDNO2 = RRAND4(DUMMY)
      GO TO 822
  820 RRDNO1 = RRAND5(DUMMY)
  821 RRDNO2 = RRAND5(DUMMY)
C     GENERATE NEXT RAMP HEADWAY
  822 RH = RAMP(RRDNO1,RRDNO2,RA1,RT1,RD1,RA2,RT2,RD2)
C     CALCULATE RAMP ARRIVAL TIME
      IF (I-1) 825,825,826
  825 RAT(1) = RH
      GO TO 840
  826 RAT(I) = RAT(I-1) + RH
C     DETERMINE IF QUEUE EXISTS
  827 IF(RAT(I)-RELTIM(I-1))832,828,828
  828 IF(RAT(I)-RDT(I-1))829,840,840
  829 IC = 2
C     QUEUE EXISTS
C     CALCULATE TERMINATION-OF-WAIT TIME
      TRWAIT(I) = RDT(I-1)
C     CALCULATE ARRIVAL TIME AT 1ST-IN-LINE POSITION
  830 RATFQ(I) = TRWAIT(I)
  831 GO TO 834
  832 IC=2
C     QUEUE EXISTS
C     CALCULATE TERMINATION-OF=WAIT TIME
      TRWAIT(I) = RDT(I-1)
C     CALCULATE ARRIVAL TIME AT 1ST-IN-LINE POSITION
  833 RATFQ(I) = TRWAIT(I)-CLEAR+PIEV+HOP
C     CALCULATE POSSIBLE TIME OF ENTRY INTO LAG
  834 SFGT = RATFQ(I)+BEGTIM
```

```
C      ASSUME DRIVER FACES LAG
  836 LAG = 1
  838 GO TO 846
  840 IC=1
C      NO QUEUE EXISTS
C      CALCULATE TERMINATION-OF-WAIT TIME
      TRWAIT(I) = RAT(I)
C      CALCULATE ARRIVAL TIME AT 1ST-IN-LINE POSITION
  842 RATFQ(I)=TRWAIT(I)
C      CALCULATE POSSIBLE TIME OF ENTRY INTO LAG
  844 SFGT = RATFQ(I)+BEGTIM
C      ASSUME DRIVER FACES LAG
  845 LAG = 1
C      DETERMINE IF LAG EXISTS IN SHOULDER LANE
C      IF LAG EXISTS, DRIVER FACES LAG.  IF NOT HE FACES GAP.
  846 IF(SFGT-SAT2) 868,848,848
C      CALL IN RANDOM NUMBER TO SAMPLE
C      SHOULDER LANE HEADWAY DISTRIBUTION
  848 GO TO (850,852,854,856,858),NOSIMS
  850 SRDNO = SRAND1(DUMMY)
      GO TO 860
  852 SRDNO = SRAND2(DUMMY)
      GO TO 860
  854 SRDNO = SRAND3(DUMMY)
      GO TO 860
  856 SRDNO = SRAND4(DUMMY)
      GO TO 860
  858 SRDNO = SRAND5(DUMMY)
C      GENERATE NEXT SHOULDER LANE HEADWAY
  860 SH=SHLANE(SRDNO, SHLVOL, D, Z)
C      INCREMENT SHOULDER LANE VOLUME COUNTER
  861 NSVEH=NSVEH + 1
C      UP-DATE SHOULDER-LANE ARRIVAL TIMES
  862 SAT1=SAT2
  864 SAT2=SAT2 + SH
  866 GO TO 846
C      CALCULATE LENGTH OF AVAILABLE GAP
  868 ASG=SAT2-SFGT
C      CALL IN RANDOM NUMBER TO SAMPLE ACCEPTANCE
C      DISTRIBUTION
  870 ARDNO = ARAND(DUMMY)
C      DETERMINE IF GAP IS ACCEPTABLE
  872 CALL ACCEPT (ASG, ARDNO, ACPTNO)
  874 IF (ACPTNO) 880, 880, 876
C      CALCULATE POSSIBLE TIME OF ENTRY INTO GAP
  876 SFGT=SAT2
  877 LAG = 0
```

```
C     DRIVER FACES GAP
  878 GO TO 848
C     DETERMINE VARIOUS TIME INDICES
  880 IF(LAG-1)881,882,882
C     CALCULATE RELEASE TIME
  881 RELTIM(I) = SFGT-BEGTIM+0.5
      GO TO 883
C     CALCULATE RELEASE TIME
  882 RELTIM(I) = SFGT-BEGTIM
C     CALCULATE DEPARTURE TIME
  883 RDT(I) = RELTIM(I)+CLEAR
C     INCREMENT RAMP VOLUME COUNTER
  884 NRDEPT=NRDEPT +1
C     UP-DATE TIME CLOCK
  886 TIME = RDT(I)/3600.
C     DETERMINE IF RUNNING TIME LIMIT HAS BEEN EXCEED.
C     IF IT HAS BEEN, OUTPUT TRAFFIC
C     CONDITIONS AND STOP MESSAGE
  887 IF(TIME-TIMMAX) 888, 889, 889
C     DETERMINE IF SIMULATOR LOADING IS COMPLETED
  888 IF(I-300) 800,11,11
  889 XNSVEH=NSVEH
  890 SHLVPH=XNSVEH/TIME
  891 XNRDEP=NRDEPT
  892 RAMVPH = XNRDEP/TIME
  893 WRITE (6,401)
  894 WRITE (6,403) NSVEH, SHLVPH, NRDEPT, RAMVPH, TIME
  895 WRITE (6,896)
  896 FORMAT (1HO,/////,13X,
     148HSIMULATION RUN TERMINATED DURING LOADING OF RAMP,
     21X,47HAREA PREVIOUS TO OBSERVATION OF RAMP OPERATION./
     313X,39HRE-RUN USING A RAMP VOLUME EQUAL TO THE,
     41X,33HOBSERVED RAMP VOLUME OF THIS RUN.)
  898 GO TO 500
```

```
C     BEGIN SIMULATION OF 1000 VEHICLES FOR OBSERVATION
C     CALL IN 2 RANDOM NUMBERS TO SAMPLE RAMP HEADWAY DIST.

   11 GO TO (12,14,16,18,20),NOSIMS
   12 RRDNO1 = RRAND1(DUMMY)
   13 RRDNO2 = RRAND1(DUMMY)
      GO TO 22
   14 RRDNO1 = RRAND2(DUMMY)
   15 RRDNO2 = RRAND2(DUMMY)
      GO TO 22
   16 RRDNO1 + RRAND3(DUMMY)
   17 RRDNO2 = RRAND3(DUMMY)
      GO TO 22
   18 RRDNO1 = RRAND4(DUMMY)
   19 RRDNO2 = RRAND4(DUMMY)
      GO TO 22
   20 RRDNO1 = RRAND5(DUMMY)
   21 RRDNO2 = RRAND5(DUMMY)

C     GENERATE NEXT RAMP HEADWAY
   22 RH = RAMP(RRDNO1,RRDNO2,RA1,RT1,RD1,RA2,RT2,RD2)

C     INCREMENT TOTAL VEHICLE COUNTER
   24 I=I+1

C     INCREMENT OBSERVED VEHICLE COUNTER
      L = L + 1
C     CALCULATE RAMP ARRIVAL TIME
   30 RAT(I)=RAT(I-1)+RH
C     DETERMINE QUEUE LENGTH
   35 DO 37 IM=1, 1500, 1
      IN = I - IM
   36 IF(RAT(I) - RDT(IN)) 37,38,38
   37 CONTINUE
C     ENTER QUEUE LENGTH IN QUEUE LENGTH SUMMARY
   38 LQ(L) = IM-1
C     ACCUMULATE SUM OF QUEUE LENGTHS
C     TO BE USED TO CALCULATE AVERAGE QUEUE LENGTH
   39 W = IM - 1
   40 WQL=WQL + W
C     DETERMINE IF QUEUE EXISTS
   50 IF(RAT(I)-RELTIM(I-1))60,52,52
   52 IF(RAT(I)-RDT(I-1))54,125,125
   54 IC = 2
C     QUEUE EXISTS
C     INCREMENT RESTRICTED VEHICLE COUNTER
      K = K+1
```

```
C       CALCULATE TERMINATION-OF-WAIT TIME
   55 TRWAIT(I) = RDT(I-1)

C       CALCULATE ARRIVAL TIME AT 1ST-IN-LINE POSITION
   56 RATFQ(I) = TRWAIT(I)
   58 GO TO 64
   60 IC = 2
C       QUEUE EXISTS
C       INCREMENT RESTRICTED VEHICLE COUNTER
   61 K = K+1

C       CALCULATE TERMINATION-OF-WAIT TIME
   62 TRWAIT(I) = RDT(I-1)
C       CALCULATE ARRIVAL TIME AT 1ST-IN-LINE POSITION
   63 RATFQ(I) = TRWAIT(I)-CLEAR+PIEV+HOP
C       CALCULATE POSSIBLE TIME OF ENTRY INTO LAG
   64 SFGT = RATFQ(I)+BEGTIM
C       ASSUME DRIVER FACES LAG
      LAG = 1
   65 GO TO 130
  125 IC=1
C       NO QUEUE EXISTS
C       INCREMENT NON-RESTRICTED VEHICLE COUNTER
  126 J=J+1
C       CALCULATE TERMINATION-OF-WAIT TIME
      TRWAIT(I) = RAT(I)
C       CALCULATE ARRIVAL TIME AT 1ST-IN-LINE POSITION
  127 RATFQ(I) = TRWAIT(I)
C       CALCULATE POSSIBLE TIME OF ENTRY INTO LAG
  128 SFGT = RATFQ(I)+BEGTIM
C       ASSUME DRIVER FACES LAG
      LAG = 1
C       DETERMINE IF LAG EXISTS IN SHOULDER LANE
C       IF LAG EXISTS, DRIVER FACES LAG.  IF NOT HE FACES GAP.
  130 IF(SFGT-SAT2)155,133,133
C       CALL IN RANDOM NUMBER TO SAMPLE
C       SHOULDER LANE HEADWAY DISTRIBUTION

  133 GO TO (134,135,136,137,138),NOSIMS
  134 SRDNO=SRAND1(DUMMY)
      GO TO 140
  135 SRDNO=SRAND2(DUMMY)
      GO TO 140
  136 SRDNO=SRAND3(DUMMY)
      GO TO 140
  137 SRDNO=SRAND4(DUMMY)
      GO TO 140
  138 SRDNO=SRAND5(DUMMY)
```

```
C      GENERATE NEXT SHOULDER LANE HEADWAY
  140 SH=SHLANE(SRDNO, SHLVOL, D, Z)

C      UP-DATE SHOULDER-LANE ARRIVAL TIMES
  143 SAT1=SAT2
  145 SAT2=SAT2+SH
C      INCREMENT SHOULDER LANE VOLUME COUNTER
  146 NSVEH=NSVEH+1
  150 GO TO 130
C      CALCULATE LENGTH OF AVAILABLE GAP
  155 ASG=SAT2-SFGT

C      CALL IN RANDOM NUMBER TO SAMPLE ACCEPTANCE DISTRIBUTION
  160 ARDNO=ARAND(DUMMY)
C      DETERMINE IF GAP IS ACCEPTABLE
  165 CALL ACCEPT(ASG,ARDNO,ACPTNO)
  170 IF(ACPTNO)200,200,171
C      CALCULATE POSSIBLE TIME OF ENTRY INTO GAP
  171 SFGT=SAT2
      LAG = 0

C      DRIVER FACES GAP
  172 GO TO 133
C      INCREMENT RAMP VOLUME COUNTER
  200 NRDEPT=NRDEPT+1
C      DETERMINE IF GAP OR LAG WAS ACCEPTED
  201 IF(LAG-1)1201,2201,2201
C      CALCULATE RELEASE TIME
 1201 RELTIM(I) = SFGT-BEGTIM+0.5
      GO TO 202
C      CALCULATE RELEASE TIME
 2201 RELTIM(I) = SFGT-BEGTIM
C      CALCULATE DEPARTURE TIME
  202 RDT(I) = RELTIM(I)+CLEAR
C      CONTINUE ACCORDING TO QUEUE CONDITION VEHICLE FOUND
C      ON RAMP UPON ARRIVAL
  203 GO TO (204,220),IC
C      UP-DATE WAIT-TIME, SERVICE-TIME, SYSTEM-TIME AND
C      DELAY-TIME SUMMARIES

  204 WAIT(L) = 0.
  205 SRTIM1(J) = RDT(I)-TRWAIT(I)
  206 ASRTM1=ASRTM1+SRTIM1(J)
  207 ASSRT1=ASSRT1+SRTIM1(J)**2.
  208 SRTIM(L) = SRTIM1(J)
  209 ASRTIM= ASRTIM + SRTIM(L)
```

```
  210 ASSRTM = ASSRTM + SRTIM(L)**2.
  211 SYSTM1(J) = RDT(I)-RAT(I)
 1211 ASYTM1 = ASYTM1+SYSTM1(J)
 2211 ASSYT1 = ASSYT1+SYSTM1(J)**2.
 3211 SYSTIM(L) = SYSTM1(J)
  212  ASYTM = ASYTM+SYSTIM(L)
  213 ASSYTM = ASSYTM + SYSTIM(L)**2.
  214 DELAY = SYSTM1(J)+TMLOSS
  215 GO TO 240

C     UP-DATE WAIT-TIME, SERVICE-TIME, SYSTEM-TIME AND
C     DELAY-TIME SUMMARIES

  220 WAIT2(K)=TRWAIT(I)-RAT(I)
  221 AWAIT2 = AWAIT2+WAIT2(K)
  222 ASWT2=ASWT2+WAIT2(K)**2.
  223 WAIT(L) = WAIT2(K)
  224 AWAIT = AWAIT + WAIT(L)
  225 ASWAIT = ASWAIT + WAIT(L)**2.
  226 SRTIM2(K)=RDT(I)-TRWAIT(I)
  227 ASRTM2=ASRTM2+SRTIM2(K)
  228 ASSRT2=ASSRT2+SRTIM2(K)**2.
  229 SRTIM(L) = SRTIM2(K)
  230 ASRTIM = ASRTIM + SRTIM(L)
  231 ASSRTM = ASSRTM + SRTIM(L)**2.
  232 SYSTM2(K) = RDT(I)-RAT(I)
  233 ASYTM2=ASYTM2+SYSTM2(K)
  234 ASSYT2=ASSYT2+SYSTM2(K)**2.
  235 SYSTIM(L) = SYSTM2(K)
  236 ASYTM = ASYTM + SYSTIM(L)
  237 ASSYTM = ASSYTM + SYSTIM(L)**2.
  238 DELAY = SYSTM2(K)+TMLOSS

C     INCREMENT DELAY-PERIOD COUNTERS
  240 CALL NVWGT(DELAY,NVW30,NVW60,
     1NVW90,NVW120,NVW150,NVW180)

C     UP-DATE TIME CLOCK
  250 TIME=RDT(I)/3600.

C     DETERMINE IF SIMULATION TIME LIMIT IS EXCEEDED
  255 IF(TIME-TIMMAX)260,515,515

C     DETERMINE IF TOTAL SAMPLE HAS BEEN OBSERVED
  260 IF(NRDEPT - 1300) 11, 264, 264
```

```
C       CALCULATE PERCENTAGES BY LENGTH OF DELAY

   264 XVW30 = NVW30
       PVW30 = (XVW30/1000.)
   265 XVW60 = NVW60
       PVW60 = (XVW60/1000.)
   266 XVW90 = NVW90
       PVW90 = (XVW90/1000.)
   267 XVW120 = NVW120
       PVW120 = (XVW120/1000.)
   268 XVW150 = NVW150
       PVW150 = (XVW150/1000.)
   269 XVW180 = NVW180
       PVW180 = (XVW180/1000.)

C       CALCULATE NUMBERS OF RESTRICTED
C       AND NON-RESTRICTED VEHICLES

   270 XK=K
   271 XJ=J

C       CALCULATE MEANS, VARIANCES AND STANDARD DEVIATIONS
C       OF WAIT-TIMES, SERVICE-TIMES, AND SYSTEM-TIMES

   272 AVWT1=0.
   273 VRWT1=0.
   274 SDWT1=0.
   275 AVWT2=AWAIT2/XK
   276 VRWT2=(ASWT2-(AWAIT2**2.)/XK)/(XK-1.)
   277 SDWT2=SQRT(VRWT2)
   278 AVWAIT=AWAIT/1000.
   279 VRWAIT=(ASWAIT-(AWAIT**2.)/1000.)/999.
   280 SDWAIT=SQRT(VRWAIT)
   281 AVSRT1=ASRTM1/XJ
   282 VRSRT1=(ASSRT1-(ASRTM1**2.)/XJ)/(XJ-1.)
   283 SDSRT1=SQRT(VRSRT1)
   284 AVSRT2=ASRTM2/XK
   285 VRSRT2=(ASSRT2-(ASRTM2**2.)/XK)/(XK-1.)
   286 SDSRT2=SQRT(VRSRT2)
   287 AVSRT=ASRTIM/1000.
   288 VRSRT = (ASSRTM-(ASRTIM**2.)/1000.)/999.
   289 SDSRT=SQRT(VRSRT)
   290 AVSYT1 = ASYTM1/XJ
   291 VRSYT1 = (ASSYT1-(ASYTM1**2.)/XJ)/(XJ-1.)
   292 SDSYT1 = SQRT(VRSYT1)
```

```
  293 AVSYT2=ASYTM2/XK
  294 VRSYT2=(ASSYT2-(ASYTM2**2.)/XK)/(XK-1.)
  295 SDSYT2=SQRT(VRSYT2)
  296 AVSYT=ASYTM/1000.
  297 VRSYT=(ASSYTM-(ASYTM**2.)/1000.)/999.
  298 SDSYT=SQRT(VRSYT)
  299 XI=1000.
  300 TOTLOS = AVSYT+TMLOSS

C     SORT WAIT-TIME, SERVICE-TIME, SYSTEM-TIME, AND
C     QUEUE-LENGTH DISTRIBUTIONS INTO AN INCREASING ORDER

  306 CALL SORT1(J,SRTIM1)
      CALL SORT1(J,SYSTM1)
  307 CALL SORT1(K,WAIT2)
  308 CALL SORT1(K,SRTIM2)
  309 CALL SORT1(K,SYSTM2)
  311 CALL SORT1(1000,SRTIM)
  312 CALL SORT1(1000,SYSTIM)
  313 CALL SORT2(LQ)

C     CALCULATE SIMULATED RAMP AND SHOULDER-LANE VOLUMES

  330 XNSVEH=NSVEH
  332 SHLVPH = (XNSVEH/SAT2)*3600.
  336 RAMVPH = (1000./(RAT(1300)-RAT(300)))*3600.

C     CALCULATE AVERAGE, MAXIMUM, AND VARIOUS PERCENTILE
C     QUEUE LENGTHS

  341 NVW=XK
  344 AVQL=WQL/1000.
  345 P85=LQ(850)
  346 P90=LQ(900)
  347 P95=LQ(950)
  350 LQMAX = LQ(1000)
```

```
C     WRITE OUTPUT FROM SIMULATION RUN
  400 WRITE(6,401)
  401 FORMAT(1H1,37X,
     144HRAMP CAPACITY ANALYSIS BY DIGITAL SIMULATION,/
     251X,17HSTOP-SIGN CONTROL)
  402 WRITE (6, 403) NSVEH, SHLVPH, NRDEPT, RAMVPH, TIME
  403 FORMAT(///1H0,54X,12HTRAFFIC DATA,//
     113X,6HNUMBER,5X,2HOF,9X,13HSHOULDER LANE,11X,6HNUMBER,
     211X,13HRAMP   VOLUME,9X,10HSIMULATION,/
     313X,13HSHOULDER LANE,12X,6HVOLUME,14X,8HOF   RAMP,/
     415X,8HVEHICLES,12X,13HVEH. PER HOUR,10X,8HVEHICLES,
     510X,13HVEH. PER HOUR,9X,10HTIME (HRS),//
     616X,I5,18X,F6.0,16X,I4,16X,F5.0,12X,F8.4,/)
  404 WRITE (6,406)J,AVQL, P85, P90, P95, LQMAX
  406 FORMAT(///1H0,47X,23HQUEUING CHARACTERISTICS,//
     113X,11HNUMBER   OF,4X,11HAVG. LENGTH,5X,
     213H85 TH PERCENT,4X,13H90 TH PERCENT,5X,
     313H95 TH PERCENT,7X,7HMAXIMUM,/
     413X,11HZERO QUEUES,4X,11HOF    QUEUE,5X,
     513HQUEUE  LENGTH,4X,13HQUEUE  LENGTH,5X,
     613HQUEUE LENGTH,4X,12HQUEUE LENGTH,//
     717X,I3,9X,F5.2,12X,F5.0,12X,F5.0,13X,F5.0,13X,I4,/)
  408 WRITE(6,410)
  410 FORMAT(///1H0,48X,22HDELAY  CHARACTERISTICS)
  411 WRITE(6,1411) TIM1,AVSYT,TIM2,CLEAR,TOTLOS
 1411 FORMAT(1H0,12X,12HTIME    LOSS,9X,13HTIME     LOSS,9X,
     112HTIME    LOSS,9X,13HTIME     LOSS,9X,9HTIME LOSS,  /
     213X,12HRAM.SPD-STOP,9X,13HBEG.STOP-EXIT,9X,
     312HEXIT-SHL.SPD,9X,13HEND STOP-EXIT,11X,5HTOTAL,//
     415X,F6.2,15X,F6.2,16X,F6.2,15X,F6.2,14X,F6.2,  // )
  412 WRITE(6,414)PVW30,PVW60,PVW90,PVW120,PVW150,PVW180
  414 FORMAT(1H0,12X,
     151HP R O B A B I L I T Y        T H A T       D E L A Y,
     27X,37HI S        G R E A T E R        T H A N,/
     313X,10H30-SECONDS,7X,10H60-SECONDS,7X,10H90-SECONDS,
     46X,11H120-SECONDS,6X,11H150-SECONDS,6X,
     511H180-SECONDS,//3X,6F17.3,/)
  416 WRITE (6,418) NVW, J, AVWAIT, AVWT2, VRWT2, SDWT2
  418 FORMAT(///1H0,12X,14HWAIT TIME DATA,//
     113X,8HNO.   OF,7X,6HNO. OF,7X,9HAVG. WAIT,8X,
     212HAVG.    WAIT,7X,12HVAR. OF WAIT,7X,12HSTD. DEV. OF/
     313X,8HVEHICLES,8X,4HZERO,8X,9HFOR   ALL,8X,
     412HFOR VEHICLES,7X,12HFOR VEHICLES,7X,12HWAIT FOR VEH/
     513X,7HWAITING,8X,5HWAITS,8X,8HVEHICLES,9X,
     612HTHAT    WAIT,7X,12HTHAT    WAIT,7X,12HTHAT    WAIT,
     7//15X,I3,11X,I3,10X,F7.2,11X,F7.2,13X,F6.2,13X,F6.2/)
  420 WRITE(6,401)
  422 WRITE(6,410)
  424 WRITE(6,426)
  426 FORMAT(1H0,12X,34HSERVICE TIME  (ZERO WAIT VEHICLES))
```

```
428 WRITE(6,430)XJ,AVSRT1,VRSRT1,SDSRT1
430 FORMAT(1H0,13X,6HNUMBER,22X,7HAVERAGE,
   121X,8HVARIANCE,21X,9HSTD. DEV.,/
   216X,2HOF,24X,7HSERVICE,21X,7HSERVICE,23X,7HSERVICE,/
   313X,8HVEHICLES,22X,4HTIME,25X,4HTIME,25X,4HTIME,//
   414X,F5.0,23X,F7.2,22X,F7.2,23X,F7.2,/)
431 FORMAT(1H0,13X,6HNUMBER,22X,7HAVERAGE,
   121X,8HVARIANCE,21X,9HSTD. DEV.,/
   216X,2HOF,24X,6HSYSTEM,22X,6HSYSTEM,24X,6HSYSTEM, /
   313X,8HVEHICLES,22X,4HTIME,25X,4HTIME,25X,4HTIME, //
   414X,F5.0,23X,F7.2,22X,F7.2,23X,F7.2, /)
432 WRITE(6,434)
434 FORMAT(/1H0,12X,32HSERVICE TIME  (WAITING VEHICLES))
436 WRITE(6,430)XK,AVSRT2,VRSRT2,SDSRT2
438 WRITE(6,440)
440 FORMAT(/1H0,12X,28HSERVICE TIME  (ALL VEHICLES))
442 WRITE(6,430)XI,AVSRT,VRSRT,SDSRT
444 WRITE(6,446)
446 FORMAT(/1H0,12X,33HSYSTEM TIME  (ZERO WAIT VEHICLES))
448 WRITE(6,431)XJ,AVSYT1,VRSYT1,SDSYT1
450 WRITE(6,452)
452 FORMAT(/1H0,12X,31HSYSTEM TIME  (WAITING VEHICLES))
454 WRITE(6,431)XK,AVSYT2,VRSYT2,SDSYT2
456 WRITE(6,458)
458 FORMAT(/1H0,12X,27HSYSTEM TIME  (ALL VEHICLES))
460 WRITE(6,431)XI,AVSYT,VRSYT,SDSYT
462 WRITE(6,464)
464 FORMAT(1H1,9X,5HINDEX,5X,4HWAIT,6X,7HSERVICE,5X,
   16HSYSTEM,5X,7HSERVICE,5X,6HSYSTEM,5X,5HTOTAL,8X,
   25HTOTAL,8X,5HQUEUE,/11X,3HFOR,6X,5HGIVEN,6X,5HGIVEN,
   36X,5HGIVEN,8X,4HZERO,7X,
   44HZERO,5X,7HSERVICE,6X,6HSYSTEM,7X,6HLENGTH, /
   510X,5HDIST.,5X,4HWAIT,7X,4HWAIT,8X,4HWAIT,8X,4HWAIT,
   67X,4HWAIT,7X,4HTIME,8X,4HTIME,8X,7HSUMMARY )
465 DO 466 I=1,1000,1
466 WRITE(6,468) I,WAIT2(I),SRTIM2(I),SYSTM2(I),SRTIM1(I),
   1SYSTM1(I),SRTIM(I),SYSTIM(I),LQ(I)
468 FORMAT(10X,I4,2F11.2,2F12.2,2F11.2,F12.2,8X,I4)
470 WRITE(6,472) RAMVOL, RA1, RT1, RD1, RA2, RT2, RD2
472 FORMAT(1H1,16X,4HRAMP,7X,7HPORTION,6X,9HAVG. FREE,
   16X,9HMIN. FREE,8X,7HPORTION,7X,9HAVG.RES.,6X,
   29HMIN. RES.,/15X,6HVOLUME,7X,4HFREE,9X,7HHEADWAY,8X,
   37HHEADWAY,7X,10HRESTRAINED,7X,7HHEADWAY,8X,7HHEADWAY,/
   416X,F5.0,7X,F4.2,10X,F5.2,10X,F4.2,12X,F4.2,11X,F5.2,
   510X,F5.2)
500 CONTINUE
510 STOP
```

```
C     CALCULATIONS FOR OUTPUT WHEN TIME LIMIT IS EXCEEDED
  515 XNSVEH = NSVEH
  516 SHLVPH = 3600.*XNSVEH/SAT2
  517 XNRDEP = NRDEPT
  518 RAMVPH = 3600.*((XNRDEP-300.)/(RDT(I)-RDT(300)))
C     OUTPUT WHEN TIME LIMIT IS EXCEEDED
  519 WRITE(6,401)
  520 WRITE(6,403) NSVEH,SHLVPH,NRDEPT,RAMVPH,TIME
  525 WRITE(6,530)
  530 FORMAT(1H0,/////,13X,
     148HSIMULATION RUN TERMINATED DUE TO TIME LIMITATION)
  535 STOP
      END


C     SUBROUTINE TO DETERMINE IF A GAP OF A GIVEN LENGTH
C     IS ACCEPTABLE TO A STOPPED FIRST-IN-LINE RAMP VEHICLE
$IBFTC ACCEPT
      SUBROUTINE ACCEPT(ASG,ARDNO,ACPTNO)
    1 IF (ASG-3.30)15,15,5
    5 PAG=1.-(EXP(-(ASG-3.30)/(6.50-3.30)))
   10 GO TO 20
   15 PAG =0.
   20 ACPTNO=ARDNO-PAG
   25 RETURN
      END


C     THE REMAINDER OF THE PROGRAM IS COMMON TO THE STOP-SIGN
C     YIELD-SIGN, AND ACCELERATION-LANE SIMULATORS AND IS
C     GIVEN IN APPENDIX B.4
```

APPENDIX B.2

Program for Simulation of Freeway On-Ramp With No Acceleration Lane and Yield-Sign Control

```
$ID    3046*012*105*300**        RF DAWSON
$EXECUTE        IBJOB
$IBJOB
$IBFTC MAIN
C
C      RAMP CAPACITY BY DIGITAL SIMULATION
C
C      NO ACCELERATION LANE -- YIELD-SIGN CONTROL
C
C      DEFINITIONS
C
C      ABSTRACT CONSTANTS -- A,B,C
C                    FOR THE DECL-ACCL WITHOUT STOP CONDITION
C                    T1+T2 = AVLTIM
C                AND RSPD*T1-0.5*DECL*T1*T1+(RSPD-DECL*T1)*T2
C                    +0.5*ACCL*T2*T2 = AVLDST
C                 OR 0.5*(ACCL+DECL)*T1*T1-AVLTIM*(ACCL+DECL)*T1
C                    +((RSPD*AVLTIM)+0.5*(ACCL*AVLTIM**2.)
C                    -AVLDST) = 0
C        THEREFORE   A = 0.5*(ACCL+DECL)
C                    B= -(AVLTIM)*(ACCL+DECL)
C                    C = ((RSPD*AVLTIM)+0.5*ACCL*AVLTIM**2.
C                        -AVLDST)
C      ACCL        = ACCELERATION RATE
C      ACPTNO      = NUMBER RETURNED BY ACCEPT,  IF ACPTNO IS
C                    MINUS OR ZERO, GAP IS ACCEPTABLE.  IF
C                    ACPTNO IS POSITIVE, GAP IS NOT ACCEPTABLE.
C      ACPT1       = NAME OF SUBROUTINE TO DETERMINE IF GAP IS
C                    ACCEPTABLE TO A VEHICLE IN THE N-TH POSI-
C                    TION THAT DOES NOT STOP AT THE STOP LINE
C      ACPT2       = NAME OF SUBROUTINE TO DETERMINE IF GAP IS
C                    ACCEPTABLE TO A STOPPED, FIRST-IN-LINE
C                    VEHICLE
C      ADELAY      = ACCUMULATED DELAY TIME
C      ARAND       = NAME OF SUBROUTINE THAT GENERATES RANDOM
C                    NUMBERS TO SAMPLE GAP ACCEPTANCE
C                    DISTRIBUTION
C      ARDNO       = RANDOM NUMBER GENERATED BY ARAND
C      ASG         = AVAILABLE SHOULDER LANE GAP
C      ASRTIM      = ACCUMULATED SERVICE TIMES OF ALL VEHICLES
C      ASRTM1      = ACCUMULATED SERVICE TIMES OF VEHICLES THAT
C                    DO NOT WAIT FOR QUEUE
C      ASRTM2      = ACCUMULATED SERVICE TIMES OF VEHICLES
C                    THAT WAIT FOR QUEUE
```

```
C       ASSRT1    = ACCUMULATED SQUARES OF SERVICE TIMES OF
C                   VEHICLES THAT DO NOT WAIT FOR QUEUE
C       ASSRT2    = ACCUMULATED SQUARES OF SERVICE TIMES OF
C                   VEHICLES THAT WAIT FOR QUEUE
C       ASSRTM    = ACCUMULATED SQUARES OF SERVICE TIMES OF
C                   ALL VEHICLES
C       ASSWT2    = ACCUMULATED SQUARES OF WAIT TIMES OF
C                   VEHICLES THAT WAIT FOR QUEUE
C       ASSYT1    = ACCUMULATED SQUARES OF SYSTEM TIMES OF
C                   VEHICLES THAT DO NOT WAIT FOR QUEUE
C       ASSYT2    = ACCUMULATED SQUARES OF SYSTEM TIMES OF
C                   VEHICLES THAT WAIT FOR QUEUE
C       ASSYTM    = ACCUMULATED SQUARES OF SYSTEM TIMES OF
C                   ALL VEHICLES
C       ASWAIT    = ACCUMULATED SQUARES OF WAIT TIMES OF ALL
C                   VEHICLES
C       ASWT2     = ACCUMULATED SQUARES OF SERVICE TIMES
C                   OF VEHICLES THAT WAIT
C       ASYTM1    = ACCUMULATED SYSTEM TIMES OF VEHICLES THAT
C                   DO NOT WAIT FOR QUEUE
C       ASYTM2    = ACCUMULATED SYSTEM TIME OF VEHICLES THAT
C                   WAIT FOR QUEUE
C       ASYTM     = ACCUMULATED SYSTEM TIMES OF ALL VEHICLES
C       AVLDST    = DISTANCE FROM POINT OF GENERATION ON RAMP
C                   TO POINT OF ENTRY INTO SHOULDER LANE
C       AVLTIM    = TIME AVAILABLE BETWEEN ARRIVAL TIME INTO
C                   SYSTEM AND EARLIEST POSSIBLE DEPARTURE
C                   TIME FROM SYSTEM
C       AVQL      = AVERAGE QUEUE LENGTH
C       AVSRT1    = AVERAGE SERVICE TIME OF VEHICLES THAT DO
C                   NOT WAIT FOR QUEUE
C       AVSRT2    = AVERAGE SERVICE TIME OF VEHICLES THAT WAIT
C                   FOR QUEUE
C       AVSRTM    = AVERAGE SERVICE TIME FO ALL VEHICLES
C       AVSYT1    = AVERAGE SYSTEM TIME OF VEHICLES THAT DO
C                   NOT WAIT FOR QUEUE
C       AVSYT2    = AVERAGE SYSTEM TIME OF VEHICLES THAT
C                   WAIT FOR QUEUE
C       AVSYTM    = AVERAGE SYSTEM TIME OF ALL VEHICLES
C       AVWAIT    = AVERAGE WAIT OF ALL VEHICLES
C       AVWT1     = AVERAGE WAIT OF VEHICLES THAT DO NOT WAIT
C                   FOR QUEUE
C       AVWT2     = AVERAGE WAIT OF VEHICLES THAT WAIT FOR
C                   QUEUE
C       AWAIT2    = ACCUMULATED WAIT TIMES OF VEHICLES THAT
C                   WAIT FOR QUEUE
C       AWAIT     = ACCUMULATED WAIT TIMES OF ALL VEHICLES
C       BRKDST    = REQUIRED BRAKING DISTANCE AT RAMP SPEED
C       BRKTIM    = TIME REQUIRED TO BRAKE FROM RAMP SPEED
C       C1ENSP    = SPEED OF RAMP VEHICLE AT POINT OF ENTRY
C                   INTO SHOULDER LANE WHEN VEHICLE IS ABLE
C                   TO ACCELERATE IMMEDIATELY UPON ARRIVAL
```

```
C      C1TIME     = TIME REQUIRED TO TRAVEL FROM POINT OF
C                   ARRIVAL ON RAMP TO POINT OF ENTRY INTO
C                   SHOULDER LANE USING IMMEDIATE ACCELERATION
C      C3DST      = DISTANCE TRAVELED IN SHOULDER LANE WHILE
C                   ACCELERATING FROM ENTRY SPEED TO SHOULDER
C                   LANE SPEED AFTER STOP ON RAMP
C      C3TIME     = TIME TO TRAVEL FROM POINT OF ARRIVAL ON
C                   RAMP TO POINT OF ENTRY INTO SHOULDER LANE
C                   WHEN VEHICLE IS REQUIRED TO STOP FOR ZERO
C                   TIME
C      C3TIM1     = TIME REQUIRED TO ACCELERATE FROM ENTRY
C                   SPEED OF ENSPD3 TO SHOULDER LANE SPEED
C                   AFTER STOP.  (TIME TO TRAVEL A DISTANCE
C                   OF C3DST)
C      C3TIM2     = TIME REQUIRED TO TRAVEL C3DST AT SHOULDER
C                   LANE SPEED
C      C3TLOS     = TIME LOSS DUE TO ACCELERATION THAT IS
C                   UNDERGONE IN THE SHOULDER LANE
C                 = C3TIM1 - C3TIM2
C      D          = MINIMUM HEADWAY IN SHOULDER LANE STREAM
C      DDELAY(I)  = DELAY INCURRED BY THE LTH OBSERVED VEHICLE
C      DECL       = DECELERATION RATE
C      DELAYM     = MEAN DELAY FOR 1000 OBSERVED VEHICLES
C      DST        = DISTANCE TRAVELED IN SHOULDER LANE WHILE
C                   ACCELERATING FROM ENTRY SPEED OF ENSPD2
C                   TO SHOULDER LANE SPEED WHEN VEHICLE DOES
C                   NOT ENTER FROM STOPPED 1ST-IN-LINE POSITION
C      DUMMY      = A DUMMY VARIABLE USED TO SATISFY FORTRAN
C                   IV RULES FOR CALLING SUBROUTINES
C      EDEPTM     = EARLIEST DEPARTURE TIME WITHOUT ENCROACH-
C                   ING UPON MINIMUM ALLOWABLE TIME SPACING TO
C                   LEADING RAMP VEHICLE
C      ENSPD1     = ENTRY SPEED OF PREVIOUS RAMP VEHICLE
C      ENSPD2     = ENTRY SPEED OF VEHICLE PRESENTLY UNDER
C                   OBSERVATION
C      ENTDST     = DISTANCE FROM 1ST-IN-LINE POSITION TO
C                   POINT OF ENTRY INTO SHOULDER LANE
C      I          = INDEX OF VEHICLE GENERATED
C      IC         = INDEX OF OPERATING CONDITION
C                   1 - IMMEDIATE ACCELERATION
C                   2 - DECELERATION-ACCELERATION
C                   3 - STOP AND START AS 1ST-IN-LINE VEHICLE
C                   4 - STOP AND START AS NTH-IN-LINE VEHICLE
C      IF         = INDEX OF FOLLOWING CONDITION
C                   1 - NOT UNDER INFLUENCE OF LEAD VEHICLE
C                   2 - FOLLOWING RAMP VEHICLE AT MIN. HEADWAY
C                   3 - FOLLOWING SHOULDER LANE VEHICLE AT
C                       MINIMUM HEADWAY
C      IQ         = INDEX OF QUEUE CONDITION
C                   1 - NO QUEUE
C                   2 - QUEUE
C      IQL1       = INDEX USED IN DETERMINING QUEUE LENGTH
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```
C       IQL2         = INDEX USED IN DETERMINING QUEUE LENGTH
C       J            = INDEX FOR VEHICLES NOT WAITING FOR QUEUE
C       K            = INDEX FOR VEHICLES WAITING FOR QUEUE
C       L            = INDEX FOR OBSERVED VEHICLES
C       LQ(L)        = QUEUE EXISTING AS LTH VEHICLE ENTERS
C                      SYSTEM
C       LQMAX        = MAXIMUM QUEUE OBSERVED
C       NOSIMS       = NUMBER OF SIMULATION RUN
C       NQ*IC*       = NUMBER OF VEHICLES BY QUEUE AND OPERATING
C                      CONDITIONS WHERE Q* AND IC* CODES ARE AS
C                      INDICATED ABOVE FOR IQ AND IC
C       NRDEPT       = NUMBER OF RAMP VEHICLE DEPARTURES
C       NSVEH        = NUMBER OF SHOULDER LANE VEHICLES GENERATED
C                      PAST RAMP ENTRANCE
C       NVW          = NUMBER OF VEHICLES THAT WAIT FOR A QUEUE
C       NVW**        = NUMBER OF VEHICLES WAITING LONGER THAN **
C                      SECONDS WHERE ** HAS VALUES OF 30, 60,
C                      90, 120, 150 AND 180
C       NVWGT        = NAME OF SUBROUTINE TO DETERMINE NUMBER OF
C                      VEHICLES BY LENGTH OF DELAY
C       PAG          = PROBABILITY OF ACCEPTING GAP
C       PIEV         = TIME FOR PERCEPTION, INTELLECTION, AND
C                      VOLITION AS INFLUENCED BY EMOTIONAL STATE
C       PVW**        = PERCENT OF VEHICLES DELAYED LONGER THAN
C                      ** SECONDS WHERE ** HAS VALUES OF 30, 60,
C                      90, 120, 150 AND 180
C       P85          = 85-TH PERCENTILE QUEUE LENGTH
C       P90          = 90-TH PERCENTILE QUEUE LENGTH
C       P95          = 95-TH PERCENTILE QUEUE LENGTH
C       QITIME       = QUEUE INDEX TIME USED TO DETERMINE LENGTH
C                      OF WAITING QUEUE AS NEW VEHICLE ARRIVES
C       RAMP HEADWAY DISTRIBUTION CONSTANTS
C                      RA1 = PORTION UNDER RESTRICTED CONDITION
C                      RT1 = MEAN RESTRICTED HEADWAY
C                      RD1 = MINIMUM RESTRICTED HEADWAY
C                      RA2 = PORTION UNDER FREE CONDITION
C                      RT2 = MEAN FREE HEADWAY
C                      RD2 = MINIMUM FREE HEADWAY
C       RAMP         = NAME OF SUBROUTINE THAT RETURNS RAMP
C                      HEADWAYS
C       RAMVOL       = RAMP VOLUME CALLED FOR ON DATA CARD
C       RAMVPH       = RAMP VOLUME GENERATED
C       RDT(I)       = TIME OF DEPARTURE OF THE ITH VEHICLE
C                      FROM THE SYSTEM
C       RH           = RAMP HEADWAY GENERATED BY RAMP SUBROUTINE
C       RPDATA       = NAME OF SUBROUTINE THAT RETURNS RA1, RT1,
C                      RD1, RA2, RT2, and RD2
C       RQACDT       = DISTANCE REQUIRED FOR ACCELERATION FROM
C                      RAMP SPEED TO SHOULDER LANE SPEED
C       RQACTM       = TIME REQUIRED FOR ACCELERATION FROM RAMP
C                      SPEED TO SHOULDER LANE SPEED
C       RRAND*       = NAMES OF SUBROUTINES THAT RETURN RANDOM
C                      NUMBERS TO SAMPLE HEADWAY DISTRIBUTIONS.
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```
C                         SINCE THERE ARE FIVE SUCH DISTRIBUTIONS
C                         * TAKES ON VALUES OF 1, 2, 3, 4, AND 5
C      RRDNO1           = A RANDOM NUMBER RETURNED BY RRAND* TO BE
C                         USED TO SELECT EITHER THE RESTRICTED OR
C                         THE FREE PORTION OF THE RAMP HEADWAY
C                         DISTRIBUTION
C      RRDNO2           = A RANDOM NUMBER RETURNED BY RRAND* TO BE
C                         USED TO SAMPLE EITHER THE RESTRICTED OR
C                         THE FREE PORTION OF THE RAMP HEADWAY
C                         DISTRIBUTION AS DEFINED BY RRDNO1
C      RSPD             = RAMP SPEED
C      SAT1             = ARRIVAL TIME OF LAST SHOULDER LANE VEHICLE
C      SAT2             = ARRIVAL TIME OF NEXT SHOULDER LANE VEHICLE
C      SDSRT1           = STD. DEV. OF SERVICE TIMES OF VEHICLES
C                         THAT DO NOT WAIT FOR A QUEUE
C      SDSRT2           = STD. DEV. OF SERVICE TIMES OF VEHICLES
C                         THAT WAIT FOR A QUEUE
C      SDSRTM           = STD. DEV. OF SERVICE TIMES OF ALL OBSERVED
C                         VEHICLES
C      SDWAIT           = STD. DEV. OF WAIT TIMES OF ALL OBSERVED
C                         VEHICLES
C      SDWT1            = STD. DEV. OF WAIT TIMES OF VEHICLES THAT
C                         DO NOT WAIT FOR A QUEUE
C      SDWT2            = STD. DEV. OF WAIT TIMES OF VEHICLES THAT
C                         WAIT FOR A QUEUE
C      SDSYT1           = STD. DEV. OF SYSTEM TIMES OF VEHICLES
C                         THAT DO NOT WAIT FOR A QUEUE
C      SDSYT2           = STD. DEV. OF SYSTEM TIMES OF VEHICLES
C                         THAT WAIT FOR A QUEUE
C      SDSYTM           = STD. DEV. OF SYSTEM TIMES OF ALL OBSERVED
C                         VEHICLES
C      SERVICE TIME     = TIME ON RAMP AS FIRST IN LINE VEHICLE
C                         WAITING FOR ACCEPTABLE GAP
C      SFGT             = TIME AT WHICH RAMP VEHICLE CAN GET TO
C                         ENTRY POINT AND FROM WHICH NEXT SHOULDER
C                         LANE ARRIVAL IS SCALED TO DETERMINE
C                         AVAILABLE SHOULDER LANE GAP
C      SH               = SHOULDER-LANE HEADWAYS RETURNED BY
C                         SHLANE
C      SHDATA           = NAME OF SUBROUTINE THAT RETURNS THE D AND
C                         Z PARAMETERS OF THE SHOULDER LANE HEADWAY
C                         DISTRIBUTION
C      SHLANE           = NAME OF SUBROUTINE THAT RETURNS
C                         SHOULDER LANE HEADWAYS
C      SHLVOL           = SHOULDER LANE VOLUME CALLED FOR
C      SHLVPH           = SHOULDER-LANE VOLUME GENERATED
C      SORT1            = NAME OF SUBROUTINE THAT PERFORMS A PUSH-
C                         DOWN SORT ON FLOATING-POINT QUANTITIES
C      SORT2            = NAME OF SUBROUTINE THAT PERFORMS A PUSH-
C                         DOWN SORT ON FIXED-POINT QUANTITIES
C      SRAND*           = NAMES OF SUBROUTINES THAT RETURN RANDOM
C                         NUMBERS TO SAMPLE SHOULDER LANE HEADWAY
C                         DISTRIBUTIONS.  SINCE THERE ARE FIVE SUCH
```

```
C                   DISTRIBUTIONS, * TAKES A VALUE OF 1, 2,
C                   3, 4, AND 5
C     SRDNO       = RANDOM NUMBER RETURNED BY THE SUBROUTINE
C                   SRAND*
C     SRTIM(L)    = SERVICE TIME OF THE L-TH OBSERVED VEHICLE
C     SRTIM1(J)   = SERVICE TIME OF THE J-TH VEHICLE THAT
C                   DOES NOT WAIT FOR A QUEUE
C     SRTIM2(K)   = SERVICE TIME OF THE K-TH VEHICLE THAT
C                   WAITS FOR A QUEUE
C     SSPD        = SHOULDER LANE SPEED
C     SYSTIM(L)   = SYSTEM TIME OF THE L-TH OBSERVED VEHICLE
C     SYSTM1(J)   = SYSTEM TIME OF THE J-TH VEHICLE THAT DOES
C                   NOT WAIT FOR A QUEUE
C     SYSTM2(K)   = SYSTEM TIME OF THE K-TH VEHICLE THAT
C                   WAITS FOR A QUEUE
C     SYSTM       = TOTAL TIME A VEHICLE LOSES IN THE SYSTEM
C     TIME        = NAME OF VARIABLE USED AS CLOCK
C     TIM1        = TIME REQUIRED TO ACCELERATE FROM ENTRY
C                   SPEED OF ENSPD2 TO SHOULDER LANE SPEED
C                   AFTER DECL-ACCL BUT NO STOP.  (TIME TO
C                   TRAVEL THE DISTANCE - DST)
C     TIM2        = TIME REQUIRED TO TRAVEL THE DISTANCE. DST,
C                   AT SHOULDER LANE SPEED
C     TMLOSS      = TIME LOST DURING ACCELERATION AFTER
C                   ENTERING SHOULDER LANE
C     TIMMAX      = MAXIMUM TIME SIMULATOR CAN RUN
C     T1          = TIME OF DECELERATION FOR DECL-ACCL WITHOUT
C                   STOP CONDITION
C     T2          = TIME OF ACCELERATION FOR DECL-ACCL WITHOUT
C                   STOP CONDITION
C     VEHLTH      = VEHICLE LENGTH
C     VRSRT1      = VARIANCE OF SERVICE TIMES OF VEHICLES
C                   THAT DO NOT WAIT FOR A QUEUE
C     VRSRT2      = VARIANCE OF SERVICE TIMES OF VEHICLES
C                   THAT WAIT FOR A QUEUE
C     VRSRT       = VARIANCE OF SERVICE TIMES OF ALL OBSERVED
C                   VEHICLES
C     VRSYT1      = VARIANCE OF SYSTEM TIMES OF VEHICLES THAT
C                   DO NOT WAIT FOR A QUEUE
C     VRSYT2      = VARIANCE OF SYSTEM TIMES OF VEHICLES
C                   THAT WAIT FOR A QUEUE
C     VRSYT       = VARIANCE OF SYSTEM TIMES OF ALL OBSERVED
C                   VEHICLES
C     VRWAIT      = VARIANCE OF WAIT TIMES OF ALL OBSERVED
C                   VEHICLES
C     VRWT1       = VARIANCE OF WAIT TIMES OF VEHICLES THAT
C                   DO NOT WAIT FOR A QUEUE
C     VRWT2       = VARIANCE OF WAIT TIMES OF VEHICLES THAT
C                   WAIT FOR A QUEUE
C     W           = FLOATING POINT CONVERSION OF OBSERVED
C                   QUEUE LENGTH
C     WAIT TIME   = TIME ON RAMP WHILE IN THE N,N-1,..,4,3,
C                   AND 2 POSITIONS IN A QUEUE
```

```
C       WAIT2(K)    = WAIT TIME OF THE K-TH VEHICLE THAT WAITS
C                     FOR A QUEUE
C       WAIT(L)     = WAIT TIME OF THE L-TH OBSERVED VEHICLE
C       WQL         = SUM OF OBSERVED QUEUE LENGTHS
C       XI          = FLOATING POINT CONVERSION OF NUMBER OF
C                     VEHICLES OBSERVED
C       XJ          = FLOATING POINT CONVERSION OF TOTAL NUMBER
C                     OF VEHICLES THAT DO NOT WAIT FOR A QUEUE
C       XK          = FLOATING POINT CONVERSION OF TOTAL NUMBER
C                     OF VEHICLES THAT WAIT FOR A QUEUE
C       XNRDEP      = FLOATING POINT CONVERSION OF NUMBER OF
C                     RAMP VEHICLE DEPARTURES
C       XNSVEH      = FLOATING POINT CONVERSION OF NUMBER OF
C                     SHOULDER-LANE VEHICLES GENERATED PAST
C                     THE RAMP
C       XVW**       = FLOATING POINT CONVERSION OF NUMBER OF
C                     VEHICLES DELAYED LONGER THAN ** SECONDS
C                     WHERE ** TAKES ON VALUES OF 30,60,90,120,
C                     150, AND 180.
C       Z           = NEGATIVE OF DIFFERENCE BETWEEN MEAN AND
C                     MINIMUM SHOULDER LANE HEADWAYS




C       DIMENSION STORAGE
 1000 DIMENSION RAT(1300),RDT(1300),WAIT2(1000),WAIT(1000),
     1SRTIM1(1000),SRTIM2(1000),SRTIM(1000),SYSTM1(1000),
     2SYSTM2(1000),SYSTIM(1000),LQ(1000),DDELAY(1000)
C       BEGIN SIMULATION RUN
 1001 DO 500 NOSIMS=1,5,1
 1002 WRITE(6,1003) NOSIMS
 1003 FORMAT(1H1,14X,(9HNOSIMS = ,I1)
C       INPUT DATA FOR SIMULATION RUN
 1004 READ(5,1005) SHLVOL,RAMVOL
 1005 FORMAT(F5.0, F6.0)
 1006 WRITE(6,1007) SHLVOL,RAMVOL
 1007 FORMAT(15X,9HSHLVOL = ,F5.0,5X,9HRAMVOL = ,F5.0)
C       INITIALIZE STORAGE
        NQ1IC1=0
        NQ1IC2=0
        NQ1IC3=0
        NQ1IC4=0
        NQ2IC2=0
        NQ2IC3=0
        NQ2IC4=0
```

```
 1008 I=0
 1009 L=0
 1010 SAT1=0.
 1011 SAT2=0.
 1012 WQL=0.
 1013 J=0
 1014 K=0
 1015 NRDEPT=0
 1016 NSVEH=0
 1017 NVW30=0
 1018 NVW60=0
 1019 NVW90=0
 1020 NVW120=0
 1021 NVW150=0
 1022 NVW180=0
 1023 ASRTM1=0.
 1024 ASSRT1=0.
 1025 AWAIT2=0.
 1026 ASWT2=0.
 1027 ASRTM2=0.
 1028 ASSRT2=0.
 1029 ASYTM1=0.
 1030 ASSYT1=0.
 1031 ASYTM2=0.
 1032 ASSYT2=0.
 1033 AWAIT=0.
 1034 ASWAIT=0.
 1035 ASRTIM=0.
 1036 ASSRTM=0.
 1037 ASYTM=0.
 1038 ASSYTM=0.
      ADELAY=0.

C     CALCULATION OF PROGRAM CONSTANTS
 1039 RSPD = 44.0
 1040 SSPD = (1.47)*(52.0-0.008*SHLVOL)
 1041 ACCL = 7.5
 1042 DECL = 9.0
 1043 A = 0.5*(ACCL+DECL)
 1044 RQACTM = (SSPD-RSPD)/ACCL
 1045 RQACDT = (RSPD*RQACTM)+0.5*ACCL*(RQACTM**2.)
 1046 IF(RQACDT-200.)1047,1050,1053
 1047 C1TIME = RQACTM+(200.-RQACDT)/SSPD
 1048 C1ENSP = SSPD
 1049 GO TO 1055
 1050 C1TIME = RQACTM
 1051 C1ENSP = SSPD
 1052 GO TO 1055
 1053 C1TIME = (-RSPD+SQRT(RSPD**2.+3000.))/7.5
 1054 C1ENSP = RSPD+ACCL*C1TIME
 1055 BRKTIM = RSPD/DECL
 1056 BRKDST = 0.5*DECL*BRKTIM**2.
 1057 AVLDST = 200.
 1058 ENTDST = AVLDST-BRKDST
```

```
 1059 C3TIME = RSPD/DECL+SQRT(2.*ENTDST/ACCL)
 2059 C3ENSP = SQRT(2.*ACCL*ENTDST)
 3059 C3TIM1 = (SSPD-C3ENSP)/ACCL
 4059 C3DST = C3ENSP*C3TIM1+0.5*ACCL*C3TIM1**2.
 5059 C3TIM2 = C3DST/SSPD
 6059 C3TLOS = C3TIM1-C3TIM2
      TIMMAX = 2.*(1300./RAMVOL)
 1060 CALL RPDATA (RAMVOL, RA1, RT1, RD1, RA2, RT2, RD2)
 1061 CALL SHDATA(SHLVOL, D, Z)
C     OUTPUT CONSTANTS OF RAMP AND SHOULDER LANE HEADWAY
C     DISTRIBUTIONS
 1062 WRITE(6,1063) RAMVOL,RA1,RT1,RD1,RA2,RT2,RD2,SHLVOL,D,Z
 1063 FORMAT(15X,9HRAMVOL = ,F5.0,5X,
     16HRA1 = ,F5.3,5X,6HRT1 = F6.3,5X,6HRD1 = ,F5.2 /
     234X,6HRA2 = ,F5.3,5X,6HRT2 = ,F6.3,5X,6HRD2 = ,F5.2 /
     315X,9HSHLVOL = ,F5.0,5X,4HD = ,F4.2,8X,4HZ = ,F5.2)
C
C
C     ROUTINE TO GENERATE FLOW OF 300 PRELIMINARY VEHICLES
C     THUS LOADING THE SIMULATOR BEFORE VEHICLES FOR
C     OBSERVATION ARE GENERATED
C
C     INCREMENT TOTAL VEHICLE COUNTER
  800 I = I + 1
C     CALL IN 2 RANDOM NUMBERS TO SAMPLE RAMP HEADWAY DIST.
  810 GO TO (812,814,816,818,820),NOSIMS
  812 RRDNO1 = RRAND1(DUMMY)
  813 RRDNO2 = RRAND1(DUMMY)
      GO TO 822
  814 RRDNO1 = RRAND2(DUMMY)
  815 RRDNO2 = RRAND2(DUMMY)
      GO TO 822
  816 RRDNO1 = RRAND3(DUMMY)
  817 RRDNO2 = RRAND3(DUMMY)
      GO TO 822
  818 RRDNO1 = RRAND4(DUMMY)
  819 RRDNO2 = RRAND4(DUMMY)
      GO TO 822
  820 RRDNO1 = RRAND5(DUMMY)
  821 RRDNO2 = RRAND5(DUMMY)
C     GENERATE NEXT RAMP HEADWAY
  822 RH = RAMP(RRDNO1,RRDNO2,RA1,RT1,RD1,RA2,RT2,RD2)
C     DETERMINE IF THIS IS THE FIRST VEHICLE TO BE GENERATED
C     AND PROCEED ACCORDINGLY
      IF (I-1) 825,825,826
C     CALCULATE RAMP ARRIVAL TIME
  825 RAT(1) = RH
C     CALCULATE DEPARTURE TIME IF RAMP VEHICLE ACCELERATES
C     IMMEDIATELY UPON ARRIVAL INTO SYSTEM
 1825 RDT(I) = RAT(I)+C1TIME
C     CALCULATE EARLIEST POSSIBLE DEPARTURE TIME WITHOUT
C     OVERTAKING LEADING RAMP VEHICLE
```

```
 2825 EDEPTM = 0.
 3825 GO TO 830
C     CALCULATE RAMP ARRIVAL TIME
  826 RAT(I) = RAT(I-1) + RH
C     CALCULATE DEPARTURE TIME IF RAMP VEHICLE ACCELERATES
C     IMMEDIATELY UPON ARRIVAL INTO SYSTEM
  827 RDT(I) = RAT(I)+C1TIME
C     CALCULATE EARLIEST POSSIBLE DEPARTURE TIME WITHOUT
C     OVERTAKING LEADING RAMP VEHICLE
  828 EDEPTM = RDT(I-1)+2.0
C     DETERMINE IF QUEUE EXISTS
  829 IF(RDT(I)-RDT(I-1))864,830,830
  830 IQ=1
C     NO QUEUE EXISTS
C     DETERMINE OPERATING CHARACTERISTICS WHILE IN SYSTEM
 1830 IF(RDT(I)-EDEPTM)831,4831,4831
  831 IF=2
C     OBSERVED VEHICLE IS FOLLOWING LEADING RAMP VEHICLE
C     AT MINIMUM HEADWAY
 1831 IC=2
C     DECELERATION-ACCELERATION
C     CALCULATE RAMP DEPARTURE TIME ASSUMING VEHICLE IN
C     QUESTION WILL FOLLOW A LEADING VEHICLE AT
C     A MINIMUM HEADWAY
 2831 RDT(I) = RDT(I-1)+2.0
C     CALCULATE TIME AVAILABLE FROM TIME OF ARRIVAL ON RAMP
C     TO NEXT POSSIBLE DEPARTURE TIME
      AVLTIM = RDT(I)-RAT(I)
 3831 GO TO 832
 4831 IF = 1
C     OBSERVED VEHICLE IS NOT UNDER INFLUENCE OF A LEAD
C     VEHICLE
 5831 IC=1
C     IMMEDIATE ACCELERATION
C     DETERMINE IF LAG EXISTS IN SHOULDER LANE
C     IF ONE DOES, GO AHEAD TO DETERMINE LENGTH, IF NO LAG
C     EXISTS, GENERATE A GAP.
  832 IF(RDT(I)-SAT2)848,833,833
C     CALL IN RANDOM NUMBER TO SAMPLE
C     SHOULDER LANE HEADWAY DISTRIBUTION
  833 GO TO (834,836,838,840,842),NOSIMS
  834 SRDNO = SRAND1(DUMMY)
  835 GO TO 843
  836 SRDNO = SRAND2(DUMMY)
  837 GO TO 843
  838 SRDNO = SRAND3(DUMMY)
  839 GO TO 843
  840 SRDNO = SRAND4(DUMMY)
  841 GO TO 843
  842 SRDNO = SRAND5(DUMMY)
C     GENERATE NEXT SHOULDER LANE HEADWAY
  843 SH=SHLANE(SRDNO, SHLVOL, D, Z)
```

```
C     UP-DATE SHOULDER-LANE ARRIVAL TIMES
  844 SAT1=SAT2
  845 SAT2=SAT2 + SH
C     INCREMENT SHOULDER LANE VOLUME COUNTER
  846 NSVEH=NSVEH + 1
  847 GO TO 832
C     CALCULATE LENGTH OF AVAILABLE GAP
  848 ASG = SAT2-RDT(I)
C     CALL IN RANDOM NUMBER TO SAMPLE ACCEPTANCE
C     DISTRIBUTION
  849 ARDNO = ARAND(DUMMY)
C     DETERMINE IF GAP IS ACCEPTABLE AFTER SELECTING THE
C     PROPER DECISION MODEL DEPENDENT UPON THE
C     OPERATING CONDITION
C     IF GAP IS ACCEPTABLE, PROCEED AHEAD TO UPDATE RAMP
C     VOLUME COUNTER.  IF NOT CALCULATE NEW POSSIBLE
C     DEPARTURE TIME
  850 GO TO (851,851,853,851),IC
  851 CALL ACPT1(ASG,ARDNO,ACPTNO)
  852 GO TO 854
  853 CALL ACPT2(ASG,ARDNO,ACPTNO)
  854 IF(ACPTNO)884,884,855
  855 RDT(I) = SAT2+0.5
      IF=3
C     OBSERVED VEHICLE IS FOLLOWING A LEADING SHOULDER LANE
C     VEHICLE AT MINIMUM HEADWAY
C     DETERMINE AMOUNT OF AVAILABLE TIME TO EARLIEST
C     DEPARTURE TIME AND THE RESULTING OPERATING
C     CHARACTERISTICS.
  856 AVLTIM = RDT(I)-RAT(I)
  857 IF(AVLTIM-C3TIME)858,858,860
  858 IC=2
C     DECELERATION-ACCELERATION
  859 GO TO 833
  860 IC = 3
C     DECELERATION TO STOP AS 1ST-IN-LINE VEHICLE
  861 GO TO 833
  864 IQ=2
C     QUEUE EXISTS
C     DETERMINE AMOUNT OF AVAILABLE TIME TO EARLIEST
C     DEPARTURE TIME AND THE RESULTING OPERATING
C     CHARACTERISTICS.
  865 AVLTIM = EDEPTM-RAT(I)
  866 IF(AVLTIM-C3TIME)867,867,869
  867 IC=2
C     DECELERATION-ACCELERATION
 1867 IF=2
C     OBSERVED VEHICLE IS FOLLOWING LEADING RAMP VEHICLE
C     AT MINIMUM HEADWAY
  868 GO TO 873
  869 IC=4
C     DECELERATION TO STOP AS NTH-IN-LINE VEHICLE
  870 IF=2
```

```
C      OBSERVED VEHICLE IS FOLLOWING LEADING RAMP VEHICLE
C      AT MINIMUM HEADWAY
C      DETERMINE NEW POSSIBLE RAMP DEPARTURE TIME
  873 RDT(I) = RDT(I-1)+2.0
  874 GO TO 832
C      INCREMENT RAMP VOLUME COUNTER
  884 NRDEPT=NRDEPT + 1
C      DETERMINE SPEED OF ENTRY INTO SHOULDER LANE DEPENDENT
C      UPON QUEUE CONDITION, FOLLOWING CONDITION, AND
C      OPERATING CONDITION
  885 GO TO (1886,1888,1903,1905),IC
 1886 ENSPD2 = C1ENSP
 1887 GO TO 1914
 1888 B=-AVLTIM*(ACCL+DECL)
 1889 C = RSPD*AVLTIM+0.5*ACCL*(AVLTIM**2.)-AVLDST
 1890 T1 = (-B-SQRT(B*B-4.*A*C))/(2.*A)
 1891 T2 = AVLTIM-T1
 1892 ENSPD2 = RSPD-DECL*T1+ACCL*T2
 1893 GO TO (1894,1897),IQ
 1894 IF(ENSPD2-SSPD)1914,1895,1895
 1895 ENSPD2 = SSPD
 1896 GO TO 1914
 1897 GO TO (1898,1898,1899),IF
 1898 IF(ENSPD2-ENSPD1)1900,1900,1899
 1899 ENSPD2 = ENSPD1
 1900 IF(ENSPD2-SSPD)1914,1901,1901
 1901 ENSPD2 = SSPD
 1902 GO TO 1914
 1903 ENSPD2 = C3ENSP
 1904 GO TO 1914
 1905 ENSPD2 = ENSPD1
 1906 IF(ENSPD2-SSPD)1914,1907, 1907
 1907 ENSPD2 = SSPD
C      SINCE VEHICLE IS LEAVING SYSTEM DEFINE IT TO BE THE
C      PREVIOUS VEHICLE AND ESTABLISH PREVIOUS-VEHICLE
C      ENTERING SPEED
 1914 ENSPD1 = ENSPD2
C      UP-DATE TIME CLOCK
  886 TIME = RDT(I)/3600.
C      DETERMINE IF RUNNING TIME LIMIT HAS BEEN EXCEED.
C      IF IT HAS BEEN, OUTPUT TRAFFIC CONDITIONS AND STOP
C      MESSAGE
  887 IF(TIME-TIMMAX) 888,889,889
C      DETERMINE IF SIMULATOR LOADING IS COMPLETED
  888 IF(I-300)800,900,900
C      OUTPUT TRAFFIC DATA AND INFORMATION MESSAGE WHEN THE
C      TIME LIMIT IS EXCEEDED
  889 XNSVEH=NSVEH
  890 SHLVPH=XNSVEH/TIME
  891 XNRDEP=NRDEPT
  892 RAMVPH = XNRDEP/TIME
  893 WRITE (6,401)
  894 WRITE (6,403) NSVEH, SHLVPH, NRDEPT, RAMVPH, TIME
```

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  895 WRITE (6,896)
  896 FORMAT (1HO,/////,13X,
     148HSIMULATION RUN TERMINATED DURING LOADING OF RAMP,
     21X,47HAREA PREVICUS TO OBERSVATION OF RAMP OPERATION./
     313X,39HRE-RUN USING A RAMP VOLUME EQUAL TO THE,
     41X,33HOBSERVED RAMP VOLUME OF THIS RUN.)
  898 GO TO 500
C     BEGIN SIMULATION OF 1000 VEHICLES FOR OBSERVATION
C     CALL IN 2 RANDOM NUMBERS TO SAMPLE RAMP HEADWAY DIST.
  900 GO TO (901,903,905,907,909),NOSIMS
  901 RRDNO1 = RRAND1(DUMMY)
  902 RRDNO2 = RRAND1(DUMMY)
      GO TO 915
  903 RRDNO1 = RRAND2(DUMMY)
  904 RRDNO2 = RRAND2(DUMMY)
      GO TO 915
  905 RRDNO1 = RRAND3(DUMMY)
  906 RRDNO2 = RRAND3(DUMMY)
      GO TO 915
  907 RRDNO1 = RRAND4(DUMMY)
  908 RRDNO2 = RRAND4(DUMMY)
      GO TO 915
  909 RRDNO1 = RRAND5(DUMMY)
  910 RRDNO2 = RRAND5(DUMMY)
C     GENERATE NEXT RAMP HEADWAY
  915 RH = RAMP(RRDNO1,RRDNO2,RA1,RT1,RD1,RA2,RT2,RD2)
C     INCREMENT TOTAL VEHICLE COUNTER
  916 I = I + 1
C     INCREMENT OBSERVED VEHICLE COUNTER
  917 L = L + 1
C     CALCULATE RAMP ARRIVAL TIME
    1 RAT(I) = RAT(I-1)+RH
C     CALCULATE DEPARTURE TIME IF RAMP VEHICLE ACCELERATED
C     IMMEDIATELY UPON ARRIVAL INTO SYSTEM
    2 RDT(I) = RAT(I)+C1TIME
C     CALCULATE EARLIEST POSSIBLE DEPARTURE TIME WITHOUT
C     OVERTAKING LEADING RAMP VEHICLE
    3 EDEPTM = RDT(I-1)+2.0
C     DETERMINE IF QUEUE EXISTS
    4 IF(RDT(I)-RDT(I-1))80,6,6
    6 IQ=1
C     NO QUEUE EXISTS
C     DETERMINE OPERATING CHARACTERISTICS WHILE IN SYSTEM
 1116 IF(RDT(I)-EDEPTM)7,4117,4117
    7 IF=2
C     OBSERVED VEHICLE IS FOLLOWING LEADING RAMP VEHICLE
C     AT MINIMUM HEADWAY
 1117 IC=2
C     DECELERATION-ACCELERATION
C     CALCULATE RAMP DEPARTURE TIME ASSUMING VEHICLE IN
C     QUESTION WILL FOLLOW A LEADING VEHICLE AT
C     A MINIMUM HEADWAY
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 2117 RDT(I) = RDT(I-1)+2.0
C       CALCULATE TIME AVAILABLE FROM TIME OF ARRIVAL ON RAMP
C       TO NEXT POSSIBLE DEPARTURE TIME
        AVLTIM = RDT(I)-RAT(I)
 3117 GO TO 8
 4117 IF=1
C       OBSERVED VEHICLE IS NOT UNDER INFLUENCE OF A LEAD
C       VEHICLE
 5117 IC=1
C       IMMEDIATE ACCELERATION
C       INCREMENT NON-RESTRICTED VEHICLE COUNTER
    8 J=J+1
C       ENTER QUEUE LENGTH IN QUEUE LENGTH SUMMARY
    9 LQ(L)=0
C       DETERMINE IF LAG EXISTS IN SHOULDER LANE
C       IF ONE DOES, GO AHEAD TO DETERMINE LENGTH.  IF NO LAG
C       EXISTS, GENERATE A GAP.
   12 IF(RDT(I)-SAT2)36,14,14
C       CALL IN RANDOM NUMBER TO SAMPLE
C       SHOULDER LANE HEADWAY DISTRIBUTION
   14 GO TO (16,18,20,22,24),NOSIMS
   16 SRDNO=SRAND1(DUMMY)
   17 GO TO 26
   18 SRDNO=SRAND2(DUMMY)
   19 GO TO 26
   20 SRDNO=SRAND3(DUMMY)
   21 GO TO 26
   22 SRDNO=SRAND4(DUMMY)
   23 GO TO 26
   24 SRDNO=SRAND5(DUMMY)
C       GENERATE NEXT SHOULDER LANE HEADWAY
   26 SH=SHLANE(SRDNO, SHLVOL, D, Z)
C       UP-DATE SHOULDER-LANE ARRIVAL TIMES
   28 SAT1=SAT2
   30 SAT2=SAT2+SH
C       INCREMENT SHOULDER LANE VOLUME COUNTER
   32 NSVEH=NSVEH+1
   34 GO TO 12
C       CALCULATE LENGTH OF AVAILABLE GAP
   36 ASG = SAT2-RDT(I)
C       CALL IN RANDOM NUMBER TO SAMPLE ACCEPTANCE
C       DISTRIBUTION
   37 ARDNO=ARAND(DUMMY)
C       DETERMINE IF GAP IS ACCEPTABLE AFTER SELECTING THE
C       PROPER DECISION MODEL DEPENDENT UPON THE
C       OPERATING CONDITION
C       IF GAP IS ACCEPTABLE, PROCEED AHEAD TO UPDATE RAMP
C       VOLUME COUNTER.  IF NOT CALCULATE NEW POSSIBLE
C       DEPARTURE TIME
   38 GO TO (39,39,41,39),IC
   39 CALL ACPT1(ASG,ARDNO,ACPTNO)
   40 GO TO 42
```

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   41 CALL ACPT2(ASG,ARDNO,ACPTNO)
   42 IF(ACPTNO)53,53,43
   43 RDT(I) = SAT2+0.5
      IF = 3
C     OBSERVED VEHICLE IS FOLLOWING A LEADING SHOULDER LANE
C     VEHICLE AT MINIMUM HEADWAY
C     DETERMINE AMOUNT OF AVAILABLE TIME TO EARLIEST
C     DEPARTURE TIME AND THE RESULTING OPERATING
C     CHARACTERISTICS.
   44 AVLTIM = RDT(I)-RAT(I)
   45 IF(AVLTIM-C3TIME)46,46,48
   46 IC=2
C     DECELERATION-ACCELERATION
   47 GO TO 14
   48 IC = 3
C     DECELERATION TO STOP AS 1ST-IN-LINE VEHICLE
   49 GO TO 14
C     INCREMENT RAMP VOLUME COUNTER
   53 NRDEPT = NRDEPT+1
C     PROCEED DEPENDENT UPON QUEUE AND OPERATING CONDITIONS
   54 GO TO (55,100),IQ
   55 GO TO (56,60,75),IC
C     UPDATE QUEUE-OPERATING CONDITION COUNTER
   56 NQ1IC1 = NQ1IC1+1
C     CALCULATE ENTERING SPEED
   57 ENSPD2 = C1ENSP
C     CALCULATE ACCELERATION TIME LOSS
   58 TMLOSS = 0.
   59 GO TO 203
C     UPDATE QUEUE-OPERATING CONDITION COUNTER
   60 NQ1IC2 = NQ1IC2+1
C     CALCULATE ENTERING SPEED
   61 B = -AVLTIM*(ACCL+DECL)
   62 C = RSPD*AVLTIM+0.5*ACCL*(AVLTIM**2.)-AVLDST
   63 T1 = (-B-SQRT(B*B-4.*A*C))/(2.*A)
   64 T2 = AVLTIM-T1
   65 ENSPD2 = RSPD-DECL*T1+ACCL*T2
   66 IF(ENSPD2-SSPD)70,67,67
   67 ENSPD2 = SSPD
C     CALCULATE ACCELERATION TIME LOSS
   68 TMLOSS = 0.
   69 GO TO 203
C     CALCULATE ACCELERATION TIME LOSS
   70 TIM1 = (SSPD-ENSPD2)/ACCL
   71 DST = ENSPD2*TIM1+0.5*ACCL*TIM1**2.
   72 TIM2 = DST/SSPD
   73 TMLOSS = TIM1-TIM2
   74 GO TO 203
C     UPDATE QUEUE-OPERATING CONDITION COUNTER
   75 NQ1IC3 = NQ1IC3+1
C     CALCULATE ENTERING SPEED
   76 ENSPD2 = C3ENSP
```

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C       CALCULATE ACCELERATION TIME LOSS
   77 TMLOSS = C3TLOS
C       SINCE VEHICLE IS LEAVING SYSTEM DEFINE IT TO BE THE
C       PREVIOUS VEHICLE AND ESTABLSIH PREVIOUS-VEHICLE
C       ENTERING SPEED
  203 ENSPD1 = ENSPD2
C       UP-DATE WAIT-TIME, SERVICE-TIME, SYSTEM-TIME AND
C       DELAY-TIME SUMMARIES
  204 WAIT(L) = 0.
  205 SRTIM1(J) = RDT(I)-(RAT(I)+C1TIME)
  206 ASRTM1=ASRTM1+SRTIM1(J)
  207 ASSRT1=ASSRT1+SRTIM1(J)**2.
  208 SRTIM(L) = SRTIM1(J)
  209 ASRTIM = ASRTIM + SRTIM(L)
  210 ASSRTM = ASSRTM + SRTIM(L)**2.
  211 SYSTM1(J) = RDT(I)-(RAT(I)+C1TIME)
  212 ASYTM1 = ASYTM1+SYSTM1(J)
  213 ASSYT1 = ASSYT1+SYSTM1(J)**2.
  214 SYSTIM(L) = SYSTM1(J)
  215 ASYTM = ASYTM+SYSTIM(L)
  216 ASSYTM = ASSYTM + SYSTIM(L)**2.
  217 DELAY = SYSTM1(J)+TMLOSS
 1217 ADELAY = ADELAY+DELAY
 2217 DDELAY(L) = DELAY
  218 GO TO 240
   80 IQ=2
C       QUEUE EXISTS
C       INCREMENT RESTRICTED VEHICLE COUNTER
   81 K=K+1
C       DETERMINE AMOUNT OF AVAILABLE TIME TO EARLIEST
C       DEPARTURE TIME
   82 AVLTIM = EDEPTM-RAT(I)
C       DETERMINE QUEUE LENGTH
   83 QITIME = RAT(I)+C1TIME
   84 DO 87 IQL1=1,1300,1
   85 IQL2 = I-IQL1
   86 IF(QITIME-RDT(IQL2))87,87,88
   87 CONTINUE
C       ENTER QUEUE LENGTH IN QUEUE LENGTH SUMMARY
   88 LQ(L) = IQL1-1
C       ACCUMULATE SUM OF QUEUE LENGTHS
   89 W = IQL1-1
   90 WQL = WQL+W
C       DETERMINE OPERATING CHARACTERISTICS
   91 IF(AVLTIM-C3TIME)92,92,95
   92 IC=2
C       DECELERATION-ACCELERATION
   93 IF=2
C       OBSERVED VEHICLE IS FOLLOWING LEADING RAMP VEHICLE
C       AT MINIMUM HEADWAY
   94 GO TO 98
   95 IC=4
```

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C       DECELERATION TO STOP AS NTH-IN-LINE VEHICLE
   96 IF=2
C       OBSERVED VEHICLE IS FOLLOWING LEADING RAMP VEHICLE
C       AT MINIMUM HEADWAY
C       DETERMINE NEW POSSIBLE RAMP DEPARTURE TIME
   98 RDT(I) = RDT(I-1)+2.0
   99 GO TO 12
C       PROCEED DEPENDENT UPON OPERATING CONDITION
  100 GO TO (102,102,104,106),IC
C       UPDATE QUEUE-OPERATING CONDITION COUNTER
  102 NQ2IC2=NQ2IC2+1
C       CALCULATE ENTERING SPEED
 1102 B = -AVLTIM*(ACCL+DECL)
 2102 C= RSPD*AVLTIM+0.5*ACCL*(AVLTIM**2.)-AVLDST
 3102 T1 = (-B-SQRT(B*B-4.*A*C))/(2.*A)
 4102 T2 = AVLTIM-T1
 5102 ENSPD2 = RSPD-DECL*T1+ACCL*T2
  115 GO TO (116,116,117),IF
  116 IF(ENSPD2-ENSPD1)118,118,117
  117 ENSPD2 = ENSPD1
  103 GO TO 118
C       UPDATE QUEUE-OPERATING CONDITION COUNTER
  104 NQ2IC3 = NQ2IC3+1
C       CALCULATE ENTERING SPEED
 2104 ENSPD2 = C3ENSP
C       CALCULATE ACCELERATION TIME LOSS
 3104 TMLOSS = C3TLOS
  105 GO TO 219
C       UPDATE QUEUE-OPERATING CONDITION COUNTER
  106 NQ2IC4 = NQ2IC4+1
C       CALCULATE ENTERING SPEED
  107 ENSPD2 = ENSPD1
  118 IF(ENSPD2-SSPD)122,119,119
  119 ENSPD2 = SSPD
C       CALCULATE ACCELERATION TIME LOSS
  120 TMLOSS = 0.
  121 GO TO 219
C       CALCULATE ACCELERATION TIME LOSS
  122 TIM1 = (SSPD-ENSPD2)/ACCL
  123 DST = ENSPD2*TIM1+0.5*ACCL*(TIM1**2.)
  124 TIM2 = DST/SSPD
  125 TMLOSS = TIM1-TIM2
C       SINCE VEHICLE IS LEAVING SYSTEM DEFINE IT TO BE THE
C       PREVIOUS VEHICLE AND ESTABLISH PREVIOUS-VEHICLE
C       ENTERING SPEED
  219 ENSPD1 = ENSPD2
C       UP-DATE WAIT-TIME, SERVICE-TIME, SYSTEM-TIME AND
C       DELAY-TIME SUMMARIES
  220 WAIT2(K) = RDT(I-1)-(RAT(I)+C1TIME)
  221 AWAIT2 = AWAIT2+WAIT2(K)
  222 ASWT2=ASWT2+WAIT2(K)**2.
  223 WAIT(L) = WAIT2(K)
  224 AWAIT = AWAIT + WAIT(L)
  225 ASWAIT = ASWAIT + WAIT(L)**2.
```

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  226 SRTIM2(K) = RDT(I)-RDT(I-1)
  227 ASRTM2=ASRTM2+SRTIM2(K)
  228 ASSRT2=ASSRT2+SRTIM2(K)**2.
  229 SRTIM(L) = SRTIM2(K)
  230 ASRTIM = ASRTIM + SRTIM(L)
  231 ASSRTM = ASSRTM + SRTIM(L)**2.
  232 SYSTM2(K) = RDT(I)-(RAT(I)+C1TIME)
  233 ASYTM2=ASYTM2+SYSTM2(K)
  234 ASSYT2=ASSYT2+SYSTM2(K)**2.
  235 SYSTIM(L) = SYSTM2(K)
  236 ASYTM = ASYTM + SYSTIM(L)
  237 ASSYTM = ASSYTM + SYSTIM(L)**2.
  238 DELAY = SYSTM2(K)+TMLOSS
 1238 ADELAY = ADELAY+DELAY
 2238 DDELAY(L) = DELAY
C     INCREMENT DELAY-PERIOD COUNTERS
  240 CALL NVWGT(DELAY,NVW30,NVW60,
     1NVW90,NVW120,NVW150,NVW180)
C     UP-DATE TIME CLOCK
  250 TIME=RDT(I)/3600.
C     DETERMINE IF SIMULATION TIME LIMIT IS EXCEEDED
  255 IF(TIME-TIMMAX)260,515,515
C     DETERMINE IF TOTAL SAMPLE HAS BEEN OBSERVED
  260 IF(NRDEPT-1300)900,264,264
C     CALCULATE PERCENTAGES BY LENGTH OF DELAY
  264 XVW30 = NVW30
      PVW30 = (XVW30/1000.)
  265 XVW60 = NVW60
      PVW60 = (XVW60/1000.)
  266 XVW90 = NVW90
      PVW90 = (XVW90/1000.)
  267 XVW120 = NVW120
      PVW120 = (XVW120/1000.)
  268 XVW150 = NVW150
      PVW150 = (XVW150/1000.)
  269 XVW180 = NVW180
      PVW180 = (XVW180/1000.)
C     CALCULATE NUMBERS OF RESTRICTED
C     AND NON-RESTRICTED VEHICLES
  270 XK=K
  271 XJ=J
C     CALCULATE MEANS, VARIANCES AND STANDARD DEVIATIONS
C     OF WAIT-TIMES, SERVICE-TIMES, AND SYSTEM-TIMES
  272 AVWT1=0.
  273 VRWT1=0.
  274 SDWT1=0.
  275 AVWT2=AWAIT2/XK
  276 VRWT2=(ASWT2-(AWAIT2**2.)/XK)/(XK-1.)
  277 SDWT2=SQRT(VRWT2)
  278 AVWAIT=AWAIT/1000.
  279 VRWAIT=(ASWAIT-(AWAIT**2.)/1000.)/999.
  280 SDWAIT=SQRT(VRWAIT)
  281 AVSRT1=ASRTM1/XJ
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  282 VRSRT1=(ASSRT1-(ASRTM1**2.)/XJ)/(XJ-1.)
  283 SDSRT1=SQRT(VRSRT1)
  284 AVSRT2=ASRTM2/XK
  285 VRSRT2=(ASSRT2-(ASRTM2**2.)/XK)/(XK-1.)
  286 SDSRT2=SQRT(VRSRT2)
  287 AVSRT=ASRTIM/1000.
  288 VRSRT = (ASSRTM-(ASRTIM**2.)/1000.)/999.
  289 SDSRT=SQRT(VRSRT)
  290 AVSYT1 = ASYTM1/XJ
  291 VRSYT1 = (ASSYT1-(ASYTM1**2.)/XJ)/(XJ-1.)
  292 SDSYT1 = SQRT(VRSYT1)
  293 AVSYT2=ASYTM2/XK
  294 VRSYT2=(ASSYT2-(ASYTM2**2.)/XK)/(XK-1.)
  295 SDSYT2=SQRT(VRSYT2)
  296 AVSYT=ASYTM/1000.
  297 VRSYT=(ASSYTM-(ASYTM**2.)/1000.)/999.
  298 SDSYT=SQRT(VRSYT)
 1298 DELAYM = ADELAY/1000.
  299 XI=1000.
C     SORT WAIT-TIME, SERVICE-TIME, SYSTEM-TIME, AND
C     QUEUE-LENGTH DISTRIBUTIONS INTO AN INCREASING ORDER
  305 CALL SORT1(J,SRTIM1)
  306 CALL SORT1(J,SYSTM1)
  307 CALL SORT1(K,WAIT2)
  308 CALL SORT1(K,SRTIM2)
  309 CALL SORT1(K,SYSTM2)
  311 CALL SORT1(1000,SRTIM)
  312 CALL SORT1(1000,SYSTIM)
  313 CALL SORT2(LQ)
  314 CALL SORT1(1000,DDELAY)
C     CALCULATE SIMULATED RAMP AND SHOULDER-LANE VOLUMES
  330 XNSVEH=NSVEH
  332 SHLVPH = (XNSVEH/SAT2)*3600.
  336 RAMVPH = (1000./(RAT(1300)-RAT(300)))*3600.
  341 NVW=XK
C     CALCULATE AVERAGE, MAXIMUM, AND VARIOUS PERCENTILE
C     QUEUE LENGTHS
  344 AVQL=WQL/1000.
  345 P85=LQ(850)
  346 P90=LQ(900)
  347 P95=LQ(950)
  350 LQMAX = LQ(1000)
C     WRITE OUTPUT FROM SIMULATION RUN
  400 WRITE(6,401)
  401 FORMAT(1H1,37X,
     144HRAMP CAPACITY ANALYSIS BY DIGITAL SIMULATION,/
     251X,18HYIELD-SIGN CONTROL)
  402 WRITE (6, 403) NSVEH, SHLVPH, NRDEPT, RAMVPH, TIME
  403 FORMAT(/ 1H0,54X,12HTRAFFIC DATA, //
     113X,6HNUMBER,5X,2HOF,9X,13HSHOULDER LANE,11X,6HNUMBER,
     211X,13HRAMP   VOLUME,9X,10HSIMULATION,/
     313X,13HSHOULDER LANE,12X,6HVOLUME,14X,8HOF   RAMP,/
     415X,8HVEHICLES,12X,13HVEH. PER HOUR,10X,8HVEHICLES,
     510X,13HVEH. PER HOUR,9X,10HTIME (HRS),//
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   616X,I5,18X,F6.0,16X,I4,16X,F5.0,12X,F8.4,/)
 404 WRITE (6,406)J,AVQL, P85,P90, P95, LQMAX
 406 FORMAT(/ 1HO,47X,23HQUEUING CHARACTERISTICS, //
   113X,11HNUMBER   OF,4X,11HAVG. LENGTH,5X,
   213H85 TH PERCENT,4X,13H90 TH PERCENT,5X,
   313H95 TH PERCENT,7X,7HMAXIMUM,/
   413X,11HZERO QUEUES,4X,11HOF    QUEUE,5X,
   513HQUEUE  LENGTH,4X,13HQUEUE  LENGTH,5X,
   613HQUEUE  LENGTH,4X,12HQUEUE LENGTH,//
   717X,I3,9X,F5.2,12X,F5.0,12X,F5.0,13X,F5.0,13X,I4,/)
 408 WRITE(6,410)
 410 FORMAT(/1HO,48X,22HDELAY  CHARACTERISTICS )
 412 WRITE(6,414)PVW30,PVW60,PVW90,PVW120,PVW150,PVW180
 414 FORMAT(1HO,12X,
   151HP R O B A B I L I T Y     T H A T     D E L A Y,
   27X,37HI S      G R E A T E R     T H A N,/
   313X,10H30-SECONDS,7X,10H60-SECONDS,7X,10H90-SECONDS,
   46X,11H120-SECONDS,6X,11H150-SECONDS,6X,
   511H180-SECONDS,//3X,6F17.3,/)
 415 WRITE(6,1415)C1TIME,DELAYM,C3TIME
1415 FORMAT( / ,1HO,12X,21HSYSTEM TIME CONSTANTS, //
   113X,41HTIME FOR IMMEDIATE ACCELERATION CONDITION,
   27X,10HAVG. DELAY,8X,
   329HTIME FOR EXACT STOP CONDITION,   //
   430X,F6.2,27X,F6.2,24X,F6.2)
 419 WRITE(6,1419) NQ1IC1,NQ1IC2,NQ1IC3,NQ2IC2,NQ2IC3,NQ2IC4
1419 FORMAT(/ 1HO,12X,
   143HNUMBERS OF VEHICLES BY OPERATING CONDITIONS, //
   230X,8HNO QUEUE,21X,3H+++,22X,5HQUEUE,  /
   314X,9HIMMEDIATE,6X,12HDECELERATION,8X,4HSTOP,
   411X,12HDECELERATION,5X,10HSTOP VEH 1,6X,10HSTOP VEH N/
   513X,12HACCELERATION,4X,12HACCELERATION,4X,
   612HACCELERATION,7X,12HACCELERATION,4X,
   712HACCELERATION,4X,12HACCELERATION,  //
   84X,3I16,3X,3I16)
 416 WRITE (6,418) NVW, J, AVWAIT,AVWT2,VRWT2,SDWT2
 418 FORMAT(/1HO,12X,14HWAIT TIME DATA,//
   113X,8HNO.   OF,7X,6HNO. OF,7X,9HAVG. WAIT,8X,
   212HAVG.   WAIT,7X,12HVAR. OF WAIT,7X,12HSTD. DEV. OF/
   313X,8HVEHICLES,8X,4HZERO,8X,9HFOR   ALL,8X,
   412HFOR VEHICLES,7X,12HFOR VEHICLES 7X,12HWAIT FOR VEH/
   513X,7HWAITING,8X,5HWAITS,8X,8HVEHICLES,9X,
   612HTHAT     WAIT,7X,12HTHAT     WAIT,7X,12HTHAT     WAIT,
   7//15X,I3,11X,I3,10X,F7.2,11X,F7.2,13X,F6.2,13X,F6.2/)
 420 WRITE(6,401)
 422 WRITE(6,410)
 424 WRITE(6,426)
 426 FORMAT(1HO,12X,34HSERVICE TIME  (ZERO WAIT VEHICLES))
 428 WRITE(6,430)XJ,AVSRT1,VRSRT1,SDSRT1
 430 FORMAT(1HO,13X,6HNUMBER,22X,7HAVERAGE,
   121X,8HVARIANCE,21X,9HSTD. DEV.,/
   216X,2HOF,24X,7HSERVICE,21X,7HSERVICE,23X,7HSERVICE,/
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   313X,8HVEHICLES,22X,4HTIME,25X,4HTIME,25X,4HTIME,//
   414X,F5.0,23X,F7.2,22X,F7.2,23X,F7.2,/)
431 FORMAT(1HO,13X,6HNUMBER,22X,7HAVERAGE,
   121X,8HVARIANCE,21X,9HSTD. DEV.,/
   216X,2HOF,24X,6HSYSTEM,22X,6HSYSTEM,24X,6HSYSTEM, /
   313X,8HVEHICLES,22X,4HTIME,25X,4HTIME,25X,4HTIME,//
   414X,F5.0,23X,F7.2,22X,F7.2,23X,F7.2,/)
432 WRITE(6,434)
434 FORMAT(/1HO,12X,32HSERVICE TIME  (WAITING VEHICLES))
436 WRITE(6,430)XK,AVSRT2,VRSRT2,SDSRT2
438 WRITE(6,440)
440 FORMAT(/1HO,12X,28HSERVICE TIME  (ALL VEHICLES))
442 WRITE(6,430)XI,AVSRT,VRSRT,SDSRT
444 WRITE(6,446)
446 FORMAT(/1HO,12X,33HSYSTEM TIME  (ZERO WAIT VEHICLES))
448 WRITE(6,431)XJ,AVSYT1,VRSYT1,SDSYT1
450 WRITE(6,452)
452 FORMAT(/1HO,12X,31HSYSTEM TIME  (WAITING VEHICLES))
454 WRITE(6,431)XK,AVSYT2,VRSYT2,SDSYT2
456 WRITE(6,458)
458 FORMAT(/1HO,12X,27HSYSTEM TIME  (ALL VEHICLES))
460 WRITE(6,431)XI,AVSYT,VRSYT,SDSYT
462 WRITE (6,464)
464 FORMAT(1H1,9X,5HINDEX,5X,4HWAIT,6X,7HSERVICE,5X,
   16HSYSTEM,5X,7HSERVICE,5X,6HSYSTEM,5X,5HTOTAL,8X,
   25HTOTAL,8X,5HQUEUE,5X,5HDELAY,  /
   311X,3HFOR,6X,5HGIVEN,6X,5HGIVEN,
   46X,5HGIVEN,8X,4HZERO,7X,
   54HZERO,5X,7HSERVICE,6X,6HSYSTEM,7X,6HLENGTH, /
   610X,5HDIST.,5X,4HWAIT,7X,4HWAIT,8X,4HWAIT,8X,4HWAIT,
   77X,4HWAIT,7X,4HTIME,8X,4HTIME,8X,7HSUMMARY,4X,5HDIST.)
465 DO 466 I=1,1000,1
466 WRITE(6,468) I,WAIT2(I),SRTIM2(I),SYSTM2(I),SRTIM1(I),
   1SYSTM1(I),SRTIM(I),SYSTIM(I),LQ(I),DDELAY(I)
468 FORMAT(10X,I4,2F11.2,2F12.2,2F11.2,F12.2,8X,I4,5X,F6.2)
470 WRITE(6,472) RAMVOL, RA1, RT1, RD1, RA2, RT2, RD2
472 FORMAT(1H1,16X,4HRAMP,7X,7HPORTION,6X,9HAVG. FREE,
   16X,9HMIN. FREE,8X,7HPORTION,7X,9HAVG.RES.,6X,
   29HMIN. RES.,/15X,6HVOLUME,7X,4HFREE,9X,7HHEADWAY,8X,
   37HHEADWAY,7X,10HRESTRAINED,7X,7HHEADWAY,8X,7HHEADWAY,/
   416X,F5.0,7X,F4.2,10X,F5.2,10X,F4.2,12X,F4.2,11X,F5.2,
   510X,F5.2)
500 CONTINUE
510 STOP
515 XNSVEH = NSVEH
516 SHLVPH = 3600.*XNSVEH/SAT2
517 XNRDEP = NRDEPT
518 RAMVPH = 3600.*((XNRDEP-300.)/(RDT(I)-RDT(300)))
519 WRITE(6,401)
520 WRITE(6,403) NSVEH,SHLVPH,NRDEPT,RAMVPH,TIME
525 WRITE(6,530)
530 FORMAT(1HO,/////,13X,
   148HSIMULATION RUN TERMINATED DUE TO TIME LIMITATION)
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  535 STOP
      END
C     SUBROUTINE TO DETERMINE IF A GAP OF A GIVEN LENGTH
C     IS ACCEPTABLE TO A MOVING RAMP VEHICLE
$IBFTC ACPT1
      SUBROUTINE ACPT1(ASG,ARDNO,ACPTNO)
    1 IF(ASG-2.0)15,15,5
    5 PAG = 1.-(EXP(-(ASG-2.0)/(5.0-2.0)))
   10 GO TO 20
   15 PAG = 0.
   20 ACPTNO = ARDNO-PAG
   25 RETURN
      END

C     SUBROUTINE TO DETERMINE IF A GAP OF A GIVEN LENGTH
C     IS ACCEPTABLE TO A STOPPED FIRST IN LINE RAMP VEHICLE
$IBFTC ACPT2
      SUBROUTINE ACPT2(ASG,ARDNO,ACPTNO)
    1 IF(ASG-3.30)15,15,5
    5 PAG = 1.-(EXP(-(ASG-3.30)/(6.50-3.30)))
   10 GO TO 20
   15 PAG = 0.
   20 ACPTNO = ARDNO-PAG
   25 RETURN
      END
C
C     THE REMAINDER OF THE PROGRAM IS COMMON TO THE STOP-SIGN,
C     YIELD-SIGN, AND ACCELERATION-LANE SIMULATORS AND IS
C     GIVEN IN APPENDIX B.4
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APPENDIX B.3

Program for Simulation of Freeway On-Ramp With Acceleration Lane and No Sign Control

```
$ID   3046*012*105*300**        RF DAWSON
$EXECUTE        IBJOB
$IBJOB
$IBFTC MAIN
C
C       RAMP CAPACITY BY DIGITAL SIMULATION
C
C       ACCELERATION LANE -- NO CONTROL
C
C       DEFINITIONS
C
C       ACCL         = ACCELERATION RATE
C       ACPTNO       = NUMBER RETURNED BY ACCEPT.  IF ACPTNO IS
C                      MINUS OR ZERO, GAP IS ACCEPTABLE.  IF
C                      ACPTNO IS POSITIVE, GAP IS NOT ACCEPTABLE.
C       ACPT1        = NAME OF SUBROUTINE TO DETERMINE IF GAP IS
C                      ACCEPTABLE TO A VEHICLE IN THE N-TH POSI-
C                      TION THAT DOES NOT STOP AT THE STOP LINE
C       ACPT2        = NAME OF SUBROUTINE TO DETERMINE IF GAP IS
C                      ACCEPTABLE TO A STOPPED, FIRST-IN-LINE
C                      VEHICLE
C       ARAND        = NAME OF SUBROUTINE THAT GENERATES RANDOM
C                      NUMBERS TO SAMPLE GAP ACCEPTANCE
C                      DISTRIBUTION
C       ARDNO        = RANDOM NUMBER GENERATED BY ARAND
C       ASG          = AVAILABLE SHOULDER LANE GAP
C       ASRTIM       = ACCUMULATED SERVICE TIMES OF ALL VEHICLES
C       ASRTM1       = ACCUMULATED SERVICE TIMES OF VEHICLES THAT
C                      DO NOT WAIT FOR QUEUE
C       ASRTM2       = ACCUMULATED SERVICE TIMES OF VEHICLES
C                      THAT WAIT FOR QUEUE
C       ASSRT1       = ACCUMULATED SQUARES OF SERVICE TIMES OF
C                      VEHICLES THAT DO NOT WAIT FOR QUEUE
C       ASSRT2       = ACCUMULATED SQUARES OF SERVICE TIMES OF
C                      VEHICLES THAT WAIT FOR QUEUE
C       ASSRTM       = ACCUMULATED SQUARES OF SERVICE TIMES OF
C                      ALL VEHICLES
C       ASSWT2       = ACCUMULATED SQUARES OF WAIT TIMES OF
C                      VEHICLES THAT WAIT FOR QUEUE
C       ASSYT1       = ACCUMULATED SQUARES OF SYSTEM TIMES OF
C                      VEHICLES THAT DO NOT WAIT FOR QUEUE
C       ASSYT2       = ACCUMULATED SQUARES OF SYSTEM TIMES OF
C                      VEHICLES THAT WAIT FOR QUEUE
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C      ASSYTM      = ACCUMULATED SQUARES OF SYSTEM TIMES OF
C                    ALL VEHICLES
C      ASWAIT      = ACCUMULATED SQUARES OF WAIT TIMES OF ALL
C                    VEHICLES
C      ASWT2       = ACCUMULATED SQUARES OF SERVICE TIMES
C                    OF VEHICLES THAT WAIT
C      ASYTM1      = ACCUMULATED SYSTEM TIMES OF VEHICLES THAT
C                    DO NOT WAIT FOR QUEUE
C      ASYTM2      = ACCUMULATED SYSTEM TIME OF VEHICLES THAT
C                    WAIT FOR QUEUE
C      ASYTM       = ACCUMULATED SYSTEM TIMES OF ALL VEHICLES
C      AVLDST      = DISTANCE FROM POINT OF GENERATION ON RAMP
C                    TO POINT OF ENTRY INTO SHOULDER LANE
C                    AT THE END OF THE ACCELERATION LANE
C      AVLTIM      = TIME AVAILABLE BETWEEN ARRIVAL TIME INTO
C                    SYSTEM AND EARLIEST POSSIBLE DEPARTURE
C                    TIME FROM SYSTEM
C      AVQL        = AVERAGE QUEUE LENGTH
C      AVSRT1      = AVERAGE SERVICE TIME OF VEHICLES THAT DO
C                    NOT WAIT FOR QUEUE
C      AVSRT2      = AVERAGE SERVICE TIME OF VEHICLES THAT WAIT
C                    FOR QUEUE
C      AVSRTM      = AVERAGE SERVICE TIME OF ALL VEHICLES
C      AVSYT1      = AVERAGE SYSTEM TIME OF VEHICLES THAT DO
C                    NOT WAIT FOR QUEUE
C      AVSYT2      = AVERAGE SYSTEM TIME OF VEHICLES THAT
C                    WAIT FOR QUEUE
C      AVSYTM      = AVERAGE SYSTEM TIME OF ALL VEHICLES
C      AVWAIT      = AVERAGE WAIT OF ALL VEHICLES
C      AVWT1       = AVERAGE WAIT OF VEHICLES THAT DO NOT WAIT
C                    FOR QUEUE
C      AVWT2       = AVERAGE WAIT OF VEHICLES THAT WAIT FOR
C                    QUEUE
C      AWAIT2      = ACCUMULATED WAIT TIMES OF VEHICLES THAT
C                    WAIT FOR QUEUE
C      AWAIT       = ACCUMULATED WAIT TIMES OF ALL VEHICLES
C      A1          = A PARAMETER OF THE ACPT1 ACCEPTANCE
C                    SUBROUTINE FOR MOVING RAMP VEHICLES
C      A2          = A PARAMETER OF THE ACPT2 ACCEPTANCE
C                    SUBROUTINE FOR STOPPED RAMP VEHICLES
C      B1          = A PARAMETER OF THE ACPT1 ACCEPTANCE
C                    SUBROUTINE FOR MOVING RAMP VEHICLES
C      B2          = A PARAMETER OF THE ACPT2 ACCEPTANCE
C                    SUBROUTINE FOR STOPPED RAMP VEHICLES
C      CRACDT      = CRITICAL ACCELERATION DISTANCE
C      CRACTM      = CRITICAL ACCELERATION TIME
C      CRDCDT      = CRITICAL DECELERATION DISTANCE
C      CRDCTM      = CRITICAL DECELERATION TIME
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C       CRSSPD     = CRITICAL SHOULDER LANE SPEED
C       C1TIME     = TIME FOR VEHICLE TO TRAVEL FROM POINT OF
C                    GENERATION TO POINT OF ENTRY INTO SHOULDER
C                    LANE AFTER IMMEDIATE ACCELERATION
C       C2TIME     = TIME FOR VEHICLE TO TRAVEL FROM POINT OF
C                    GENERATION TO POINT ENTRY INTO SHOULDER
C                    LANE AFTER MAXIMUM DELAYED ACCELERATION
C       C3TIME     = TIME FOR VEHICLE TO TRAVEL FROM POINT OF
C                    GENERATION TO POINT OF ENTRY INTO SHOULDER
C                    LANE AFTER STOPPING FOR ZERO TIME
C       D          = MINIMUM HEADWAY IN SHOULDER LANE STREAM
C       DECL       = DECELERATION RATE
C       DTRSPD     = DISTANCE TRAVELED IN SYSTEM AT RAMP SPEED
C       DTRSSS     = DISTANCE TRAVELED DURING TRANSITION FROM
C                    RAMP SPEED TO SHOULDER LANE SPEED
C       DTSSPD     = DISTANCE TRAVELED IN SYSTEM AT SHOULDER
C                    LANE SPEED
C       DUMMY      = A DUMMY VARIABLE USED TO SATISFY FORTRAN
C                    IV RULES FOR CALLING SUBROUTINES
C       EDEPTM     = EARLIEST DEPARTURE TIME WITHOUT ENCROACH-
C                    ING UPON MINIMUM ALLOWABLE TIME SPACING TO
C                    LEADING RAMP VEHICLE
C       I          = INDEX OF VEHICLE GENERATED
C       IC         = INDEX OF OPERATING CONDITION
C                    1 - IMMEDIATE ACCELERATION
C                    2 - DELAYED ACCELERATION
C                    3 - DECELERATION-ACCELERATION
C                    4 - STOP AND START AS 1-ST-IN-LINE VEHICLE
C                    5 - STOP AND START AS N-TH-IN-LINE VEHICLE
C       IQ         = INDEX OF QUEUE CONDITION
C                    1 - NO QUEUE
C                    2 - QUEUE
C       IQL1       = INDEX USED IN DETERMINING QUEUE LENGTH
C       IQL2       = INDEX USED IN DETERMINING QUEUE LENGTH
C       J          = INDEX FOR VEHICLES NOT WAITING FOR QUEUE
C       K          = INDEX FOR VEHICLES WAITING FOR QUEUE
C       L          = INDEX FOR OBSERVED VEHICLES
C       LQ(L)      = QUEUE EXISTING AS L-TH VEHICLE ENTERS
C                    SYSTEM
C       LQMAX      = MAXIMUM QUEUE OBSERVED
C       NOSIMS     = NUMBER OF SIMULATION RUN
C       NQ*IC*     = NUMBER OF VEHICLES BY QUEUE AND OPERATING
C                    CONDITIONS WHERE Q* AND IC* CODES ARE AS
C                    INDICATED ABOVE FOR IQ AND IC
C       NRDEPT     = NUMBER OF RAMP VEHICLE DEPARTURES
C       NSVEH      = NUMBER OF SHOULDER LANE VEHICLES GENERATED
C                    PAST RAMP ENTRANCE
C       NVW        = NUMBER OF VEHICLES THAT WAIT FOR A QUEUE
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C       NVW**       = NUMBER OF VEHICLES WAITING LONGER THAN **
C                     SECONDS WHERE ** HAS VALUES OF 30, 60,
C                     90, 120, 150 and 180
C       NVWGT       = NAME OF SUBROUTINE TO DETERMINE NUMBER OF
C                     VEHICLES BY LENGTH OF DELAY
C       PAG         = PROBABILITY OF ACCEPTING GAP
C       PIEV        = TIME FOR PERCEPTION, INTELLECTION, AND
C                     VOLITION AS INFLUENCED BY EMOTIONAL STATE
C       PVW**       = PERCENT OF VEHICLES DELAYED LONGER THAN
C                     ** SECONDS WHERE ** HAS VALUES OF 30, 60,
C                     90, 120, 150 AND 180
C       P85         = 85-TH PERCENTILE QUEUE LENGTH
C       P90         = 90-TH PERCENTILE QUEUE LENGTH
C       P95         = 95-TH PERCENTILE QUEUE LENGTH
C       QITIME      = QUEUE INDEX TIME USED TO DETERMINE LENGTH
C                     OF WAITING QUEUE AS NEW VEHICLE ARRIVES
C       RAMP HEADWAY DISTRIBUTION CONSTANTS
C                     RA1 = PORTION UNDER RESTRICTED CONDITION
C                     RT1 = MEAN RESTRICTED HEADWAY
C                     RD1 = MINIMUM RESTRICTED HEADWAY
C                     RA2 = PORTION UNDER FREE CONDITION
C                     RT2 = MEAN FREE HEADWAY
C                     RD2 = MINIMUM FREE HEADWAY
C       RAMP        = NAME OF SUBROUTINE THAT RETURNS RAMP
C                     HEADWAYS
C       RAMVOL      = RAMP VOLUME CALLED FOR ON DATA CARD
C       RAMVPH      = RAMP VOLUME GENERATED
C       RDT(I)      = TIME OF DEPARTURE OF THE I-TH VEHICLE
C                     FROM THE SYSTEM
C       RH          = RAMP HEADWAY GENERATED BY RAMP SUBROUTINE
C       RPDATA      = NAME OF SUBROUTINE THAT RETURNS RA1, RT1,
C                     RD1, RA2, RT2, AND RD2
C       RRAND*      = NAMES OF SUBROUTINES THAT RETURN RANDOM
C                     NUMBERS TO SAMPLE HEADWAY DISTRIBUTIONS.
C                     SINCE THERE ARE FIVE SUCH DISTRIBUTIONS
C                     * TAKES ON VALUES OF 1, 2, 3, 4, AND 5
C       RRDNO1      = A RANDOM NUMBER RETURNED BY RRAND* TO BE
C                     USED TO SELECT EITHER THE RESTRICTED OR
C                     THE FREE PORTION OF THE RAMP HEADWAY
C                     DISTRIBUTION
C       RRDNO2      = A RANDOM NUMBER RETURNED BY RRAND* TO BE
C                     USED TO SAMPLE EITHER THE RESTRICTED OR
C                     THE FREE PORTION OF THE RAMP HEADWAY
C                     DISTRIBUTION AS DEFINED BY RRDNO1
C       RSPD        = RAMP SPEED
C       SAT1        = ARRIVAL TIME OF LAST SHOULDER LANE VEHICLE
C       SAT2        = ARRIVAL TIME OF NEXT SHOULDER LANE VEHICLE
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C       SDSRT1       = STD. DEV. OF SERVICE TIMES OF VEHICLES
C                      THAT DO NOT WAIT FOR A QUEUE
C       SDSRT2       = STD. DEV. OF SERVICE TIMES OF VEHICLES
C                      THAT WAIT FOR A QUEUE
C       SDSRTM       = STD. DEV. OF SERVICE TIMES OF ALL OBSERVED
C                      VEHICLES
C       SDWAIT       = STD. DEV. OF WAIT TIMES OF ALL OBSERVED
C                      VEHICLES
C       SDWT1        = STD. DEV. OF WAIT TIMES OF VEHICLES THAT
C                      DO NOT WAIT FOR A QUEUE
C       SDWT2        = STD. DEV. OF WAIT TIMES OF VEHICLES THAT
C                      WAIT FOR A QUEUE
C       SDSYT1       = STD. DEV. OF SYSTEM TIMES OF VEHICLES
C                      THAT DO NOT WAIT FOR A QUEUE
C       SDSYT2       = STD. DEV. OF SYSTEM TIMES OF VEHICLES
C                      THAT WAIT FOR A QUEUE
C       SDSYTM       = STD. DEV. OF SYSTEM TIMES OF ALL OBSERVED
C                      VEHICLES
C       SERVICE TIME = TIME ON RAMP AS FIRST IN LINE VEHICLE
C                      WAITING FOR ACCEPTABLE GAP
C       SFGT         = TIME AT WHICH RAMP VEHICLE CAN GET TO
C                      ENTRY POINT AND FROM WHICH NEXT SHOULDER
C                      LANE ARRIVAL IS SCALED TO DETERMINE
C                      AVAILABLE SHOULDER LANE GAP
C       SH           = SHOULDER-LANE HEADWAYS RETURNED BY
C                      SHLANE
C       SHDATA       = NAME OF SUBROUTINE THAT RETURNS THE D AND
C                      Z PARAMETERS OF THE SHOULDER LANE HEADWAY
C                      DISTRIBUTION
C       SHLANE       = NAME OF SUBROUTINE THAT RETURNS
C                      SHOULDER-LANE HEADWAYS
C       SHLVOL       = SHOULDER-LANE VOLUME CALLED FOR
C       SHLVPH       = SHOULDER-LANE VOLUME GENERATED
C       SORT1        = NAME OF SUBROUTINE THAT PERFORMS A PUSH-
C                      DOWN SORT ON FLOATING-POINT QUANTITIES
C       SORT2        = NAME OF SUBROUTINE THAT PERFORMS A PUSH-
C                      DOWN SORT ON FIXED-POINT QUANTITIES
C       SRAND*       = NAMES OF SUBROUTINES THAT RETURN RANDOM
C                      NUMBERS TO SAMPLE SHOULDER LANE HEADWAY
C                      DISTRIBUTIONS.  SINCE THERE ARE FIVE SUCH
C                      DISTRIBUTIONS, * TAKES A VALUE OF 1, 2,
C                      3, 4, AND 5
C       SRDNO        = RANDOM NUMBER RETURNED BY THE SUBROUTINE
C                      SRAND*
C       SRTIM(L)     = SERVICE TIME OF THE L-TH OBSERVED VEHICLE
C       SRTIM1(J)    = SERVICE TIME OF THE J-TH VEHICLE THAT
C                      DOES NOT WAIT FOR A QUEUE
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C      SRTIM2(K)   = SERVICE TIME OF THE K-TH VEHICLE THAT
C                    WAITS FOR A QUEUE
C      SSPD        = SHOULDER LANE SPEED
C      SYSTIM(L)   = SYSTEM TIME OF THE L-TH OBSERVED VEHICLE
C      SYSTM1(J)   = SYSTEM TIME OF THE J-TH VEHICLE THAT DOES
C                    NOT WAIT FOR A QUEUE
C      SYSTM2(K)   = SYSTEM TIME OF THE K-TH VEHICLE THAT
C                    WAITS FOR A QUEUE
C      SYSTM       = TOTAL TIME A VEHICLE LOSES IN THE SYSTEM
C      TIME        = NAME OF VARIABLE USED AS CLOCK
C      TIMMAX      = MAXIMUM TIME SIMULATOR CAN RUN
C      TMACCL      = TIME TO ACCELERATE FROM STOP TO SHOULDER-
C                    LANE SPEED
C      TMRSPD      = TIME AT RAMP SPEED
C      TMRSSS      = TIME TO TRANSITION FROM RAMP SPEED TO
C                    SHOULDER-LANE SPEED
C      TMSSPD      = TIME AT SHOULDER-LANE SPEED
C      TMSTOP      = TIME TO DECELERATE TO STOP FROM RAMP SPEED
C      VEHLTH      = VEHICLE LENGTH
C      VRSRT1      = VARIANCE OF SERVICE TIMES OF VEHICLES
C                    THAT DO NOT WAIT FOR A QUEUE
C      VRSRT2      = VARIANCE OF SERVICE TIMES OF VEHICLES
C                    THAT WAIT FOR A QUEUE
C      VRSRT       = VARIANCE OF SERVICE TIMES OF ALL OBSERVED
C                    VEHICLES
C      VRSYT1      = VARIANCE OF SYSTEM TIMES OF VEHICLES THAT
C                    DO NOT WAIT FOR A QUEUE
C      VRSYT2      = VARIANCE OF SYSTEM TIMES OF VEHICLES
C                    THAT WAIT FOR A QUEUE
C      VRSYT       = VARIANCE OF SYSTEM TIMES OF ALL OBSERVED
C                    VEHICLES
C      VRWAIT      = VARIANCE OF WAIT TIMES OF ALL OBSERVED
C                    VEHICLES
C      VRWT1       = VARIANCE OF WAIT TIMES OF VEHICLES THAT
C                    DO NOT WAIT FOR A QUEUE
C      VRWT2       = VARIANCE OF WAIT TIMES OF VEHICLES THAT
C                    WAIT FOR A QUEUE
C      W           = FLOATING POINT CONVERSION OF OBSERVED
C                    QUEUE LENGTH
C      WAIT TIME   = TIME ON RAMP WHILE IN THE N,N-1,..,4,3,
C                    AND 2 POSITIONS IN A QUEUE
C      WAIT2(K)    = WAIT TIME OF THE K-TH VEHICLE THAT WAITS
C                    FOR A QUEUE
C      WAIT(L)     = WAIT TIME OF THE L-TH OBSERVED VEHICLE
C      WQL         = SUM OF OBSERVED QUEUE LENGTH
C      XI          = FLOATING POINT CONVERSION OF NUMBER OF
C                    VEHICLES OBSERVED
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C      XJ            = FLOATING POINT CONVERSION OF TOTAL NUMBER
C                      OF VEHICLES THAT DO NOT WAIT FOR A QUEUE
C      XK            = FLOATING POINT CONVERSION OF TOTAL NUMBER
C                      OF VEHICLES THAT WAIT FOR A QUEUE
C      XNRDEP        = FLOATING POINT CONVERSION OF NUMBER OF
C                      RAMP VEHICLE DEPARTURES
C      XNSVEH        = FLOATING POINT CONVERSION OF NUMBER OF
C                      SHOULDER-LANE VEHICLES GENERATED PAST
C                      THE RAMP
C      XVW**         = FLOATING POINT CONVERSION OF NUMBER OF
C                      VEHICLES DELAYED LONGER THAN ** SECONDS
C                      WHERE ** TAKES ON VALUES OF 30,60,90,120,
C                      150, AND 180.
C      Z             = NEGATIVE OF DIFFERENCE BETWEEN MEAN AND
C                      MINIMUM SHOULDER LANE HEADWAYS
C      DIMENSION STORAGE
 1000 DIMENSION RAT(1300),RDT(1300),WAIT2(1000),WAIT(1000),
     1SRTIM1(1000),SRTIM2(1000),SRTIM(1000),SYSTM1(1000),
     2SYSTM2(1000),SYSTIM(1000),LQ(1000)
```

```
C       BEGIN SIMULATION RUN
 1001 DO 500 NOSIMS=1,5,1
 1002 WRITE(6,1003) NOSIMS
 1003 FORMAT(1H1,14X,9HNOSIMS = ,I1)
C       INPUT DATA FOR SIMULATION RUN
 1004 READ(5,1005) SHLVOL,RAMVOL
 1005 FORMAT(F5.0, F6.0)
 1006 WRITE(6,1007) SHLVOL,RAMVOL
 1007 FORMAT(15X,9HSHLVOL = ,F5.0,5X,9HRAMVOL = ,F5.0)
C       INITIALIZE STORAGE
      NQ1IC1=0
      NQ1IC2=0
      NQ1IC3=0
      NQ1IC4=0
      NQ2IC2=0
      NQ2IC3=0
      NQ2IC4=0
      NQ2IC5=0
 1008 I=0
 1009 L=0
 1010 SAT1=0.
 1011 SAT2=0.
 1012 WQL=0.
 1013 J=0
 1014 K=0
 1015 NRDEPT=0
 1016 NSVEH=0
 1017 NVW30=0
 1018 NVW60=0
 1019 NVW90=0
 1020 NVW120=0
 1021 NVW150=0
 1022 NVW180=0
 1023 ASRTM1=0.
 1024 ASSRT1=0.
 1025 AWAIT2=0.
 1026 ASWT2=0.
 1027 ASRTM2=0.
 1028 ASSRT2=0.
 1029 ASYTM1=0.
 1030 ASSYT1=0.
 1031 ASYTM2=0.
 1032 ASSYT2=0.
 1033 AWAIT=0.
 1034 ASWAIT=0.
 1035 ASRTIM=0.
 1036 ASSRTM=0.
 1037 ASYTM=0.
 1038 ASSYTM=0.
```

```
C     CALCULATION OF PROGRAM CONSTANTS

 1039 RSPD = 44.0
 1040 SSPD = (1.47)*(52.0-0.008*SHLVOL)
 1041 ACCL = 7.5
 1042 DECL = 9.0
 1043 CRSSPD=1.47*52.0
 1044 CRDCTM=RSPD/DECL
 1045 CRDCDT=0.5*DECL*(CRDCTM**2.)
 1046 CRACTM=CRSSPD/ACCL
 1047 CRACDT=0.5*ACCL*(CRACTM**2.)
 1048 AVLDST=CRDCDT+CRACDT
 1049 TMRSSS=(SSPD-RSPD)/ACCL
 1050 DTRSSS=RSPD*TMRSSS+0.5*ACCL*(TMRSSS**2.)
 1051 DTSSPD=AVLDST-DTRSSS
 1052 TMSSPD=DTSSPD/SSPD
 1053 C1TIME=TMRSSS+TMSSPD
 1054 DTRSPD=AVLDST-DTRSSS
 1055 TMRSPD=DTRSPD/RSPD
 1056 C2TIME=TMRSPD+TMRSSS
 1057 TMSTOP=RSPD/DECL
 1058 TMACCL=SSPD/ACCL
 1059 C3TIME=TMSTOP+TMACCL

      TIMMAX = 2.*(1300./RAMVOL)
      B1 = 0.
      A1 = 1.00/(ALOG(4.00))
      B2 = ALOG(2.5)
      A2 = 1.00/(ALOG(8.00)-B2)

 1060 CALL RPDATA (RAMVOL, RA1, RT1, RD1, RA2, RT2, RD2)
 1061 CALL SHDATA(SHLVOL, D, Z)

C     OUTPUT CONSTANTS OF RAMP AND SHOULDER LANE HEADWAY
C     DISTRIBUTIONS

 1062 WRITE(6,1063) RAMVOL,RA1,RT1,RD1,RA2,RT2,RD2,SHLVOL,D,Z
 1063 FORMAT(15X,9HRAMVOL = ,F5.0,5X,

     16HRA1 = ,F5.3,5X,6HRT1 = F6.3,5X,6HRD1 = ,F5.2 /
     234X,6HRA2 = ,F5.3,5X,6HRT2 = ,F6.3,5X,6HRD2 = ,F5.2 /
     315X,9HSHLVOL = ,F5.0,5X,4HD = ,F4.2,8X,4HZ = ,F5.2)
```

```
C     ROUTINE TO GENERATE FLOW OF 300 PRELIMINARY VEHICLES
C     THUS LOADING THE SIMULATOR BEFORE VEHICLES FOR
C     OBSERVATION ARE GENERATED
C
C     INCREMENT TOTAL RAMP VEHICLE COUNTER
  800 I = I + 1
C
C     CALL IN 2 RANDOM NUMBERS TO SAMPLE RAMP HEADWAY DIST.
  810 GO TO (812,814,816,818,820),NOSIMS
  812 RRDNO1 = RRAND1(DUMMY)
  813 RRDNO2 = RRAND1(DUMMY)
      GO TO 822
  814 RRDNO1 = RRAND2(DUMMY)
  815 RRDNO2 = RRAND2(DUMMY)
      GO TO 822
  816 RRDNO1 = RRAND3(DUMMY)
  817 RRDNO2 = RRAND3(DUMMY)
      GO TO 822
  818 RRDNO1 = RRAND4(DUMMY)
  819 RRDNO2 = RRAND4(DUMMY)
      GO TO 822
  820 RRDNO1 = RRAND5(DUMMY)
  821 RRDNO2 = RRAND5(DUMMY)
C
C     GENERATE NEXT RAMP HEADWAY
  822 RH = RAMP(RRDNO1,RRDNO2,RA1,RT1,RD1,RA2,RT2,RD2)
C
C     DETERMINE IF THIS IS THE FIRST VEHICLE TO BE GENERATED
C     AND PROCEED ACCORDINGLY
      IF (I-1) 825,825,826
C     CALCULATE RAMP ARRIVAL TIME
  825 RAT(1) = RH
C
C     CALCULATE DEPARTURE TIME IF RAMP VEHICLE ACCELERATED
C     IMMEDIATELY UPON ARRIVAL INTO SYSTEM
 1825 RDT(I) = RAT(I)+C1TIME
C
C     CALCULATE EARLIEST POSSIBLE DEPARTURE TIME WITHOUT
C     OVERTAKING LEADING RAMP VEHICLE
 2825 EDEPTM = 0.
 3825 GO TO 830
C
C     CALCULATE RAMP ARRIVAL TIME
  826 RAT(I) = RAT(I-1) + RH
C     CALCULATE DEPARTURE TIME IF RAMP VEHICLE ACCELERATED
C     IMMEDIATELY UPON ARRIVAL INTO SYSTEM
  827 RDT(I) = RAT(I)+C1TIME
```

```
C       CALCULATE EARLIEST POSSIBLE DEPARTURE TIME WITHOUT
C       OVERTAKING LEADING RAMP VEHICLE
  828 EDEPTM = RDT(I-1)+1.8
C
C       DETERMINE IF QUEUE EXISTS
  829 IF(RDT(I)-RDT(I-1)864,830,830
  830 IQ=1
C
C       NO QUEUE EXISTS
C       DETERMINE OPERATING CHARACTERISTICS WHILE IN SYSTEM
 1830 IF(RDT(I)-EDEPTM)1831,4831,4831
 1831 IC=2
C
C       NO DECELERATION, BUT DELAYED ACCELERATION
C       CALCULATE RAMP DEPARTURE TIME ASSUMING VEHICLE IN
C       QUESTION WILL FOLLOW A LEADING VEHICLE AT
C       A MINIMUM HEADWAY
C
 2831 RDT(I) = RDT(I-1)+1.8
 3831 GO TO 832
 4831 IC=1
C
C       IMMEDIATE ACCELERATION
C       DETERMINE IF LAG EXISTS IN SHOULDER LANE
C       IF ONE DOES, GO AHEAD TO DETERMINE LENGTH.  IF NO LAG
C       EXISTS, GENERATE A GAP.
C
  832 IF(RDT(I)-SAT2)848,833,833
C       CALL IN RANDOM NUMBER TO SAMPLE
C       SHOULDER LANE HEADWAY DISTRIBUTION

  833 GO TO (834,836,838,840,842),NOSIMS
  834 SRDNO = SRAND1(DUMMY)
  835 GO TO 843
  836 SRDNO = SRAND2(DUMMY)
  837 GO TO 843
  838 SRDNO = SRAND3(DUMMY)
  839 GO TO 843
  840 SRDNO = SRAND4(DUMMY)
  841 GO TO 843
  842 SRDNO = SRAND5(DUMMY)
C
C       GENERATE NEXT SHOULDER LANE HEADWAY
  843 SH=SHLANE(SRDNO, SHLVOL, D, Z)

C       UP-DATE SHOULDER-LANE ARRIVAL TIMES
  844 SAT1=SAT2
  845 SAT2=SAT2 + SH
```

```
C       INCREMENT SHOULDER-LANE VOLUME COUNTER
  846 NSVEH=NSVEH + 1
  847 GO TO 832

C       CALCULATE LENGTH OF AVAILABLE GAP
  848 ASG = SAT2-RDT(I)

C       CALL IN RANDOM NUMBER TO SAMPLE ACCEPTANCE
C       DISTRIBUTION
  849 ARDNO = ARAND(DUMMY)

C       DETERMINE IF GAP IS ACCEPTABLE AFTER SELECTING THE
C       PROPER DECISION MODEL DEPENDENT UPON THE
C       OPERATING CONDITION
C       IF GAP IS ACCEPTABLE, PROCEED AHEAD TO UPDATE RAMP
C       VOLUME COUNTER.  IF NOT CALCULATE NEW POSSIBLE
C       DEPARTURE TIME
  850 GO TO (851,851,851,853,851),IC
  851 CALL ACPT1(ASG,ARDNO,A1,B1,ACPTNO)
  852 GO TO 854
  853 CALL ACPT2(ASG,ARDNO,A2,B2,ACPTNO)
  854 IF(ACPTNO)884,884,855
  855 RDT(I) = SAT2+0.5

C       DETERMINE AMOUNT OF AVAILABLE TIME TO EARLIEST
C       DEPARTURE TIME AND THE RESULTING OPERATING
C       CHARACTERISTICS.
  856 AVLTIM = RDT(I)-RAT(I)
  857 IF(AVLTIM-C2TIME)858,858,860
  858 IC=2

C       NO DECELERATION, BUT DELAYED ACCELERATION
  859 GO TO 833
  860 IF(AVLTIM-C3TIME)861,861,862
  861 IC=3

C       DECELERATION, FOLLOWED BY ACCELERATION WITHOUT A STOP
 1861 GO TO 833
  862 IC=4

C       DECELERATION TO STOP.  VEHICLE LEAVES FROM
C       1ST-IN-LINE POSITION
  863 GO TO 833
  864 IC=2

C       QUEUE EXISTS
```

```
C     DETERMINE AMOUNT OF AVAILABLE TIME TO EARLIEST
C     DEPARTURE TIME AND THE RESULTING OPERATING
C     CHARACTERISTICS.
  865 AVLTIM = EDEPTM-RAT(I)
  866 IF(AVLTIM-C2TIME)867,867,869
  867 IC=2
C     NO DECELERATION, BUT DELAYED ACCELERATION
  868 GO TO 873
  869 IF(AVLTIM-C3TIME)870,870,872
  870 IC=3
C     DECELERATION, FOLLOWED BY ACCELERATION WITHOUT A STOP
  871 GO TO 873
  872 IC=5
C     DECELERATION TO STOP.  VEHICLE LEAVES FROM
C     NTH-IN-LINE POSITION
C     DETERMINE NEW POSSIBLE RAMP DEPARTURE TIME
  873 RDT(I) = RDT(I-1)+1.8
  874 GO TO 832
C     INCREMENT RAMP VOLUME COUNTER
  884 NRDEPT=NRDEPT + 1
C     UP-DATE TIME CLOCK
  886 TIME = RDT(I)/3600.
C     DETERMINE IF RUNNING TIME LIMIT HAS BEEN EXCEED.
C     IF IT HAS BEEN, OUTPUT TRAFFIC DATA AND
C     INFORMATION CONCERNING STOP THAT FOLLOWS.
  887 IF(TIME-TIMMAX) 888,889,889
C     DETERMINE IF SIMULATOR LOADING IS COMPLETED
  888 IF(I-300)800,900,900
  889 XNSVEH=NSVEH
  890 SHLVPH=XNSVEH/TIME
  891 XNRDEP=NRDEPT
  892 RAMVPH = XNRDEP/TIME
  893 WRITE (6,401)
  894 WRITE (6,403) NSVEH, SHLVPH, NRDEPT, RAMVPH, TIME
  895 WRITE (6,896)
  896 FORMAT (1H0,/////,13X,
     148HSIMULATION RUN TERMINATED DURING LOADING OF RAMP,
     21X,47HAREA PREVIOUS TO OBSERVATION OF RAMP OPERATION./
     313X,39HRE-RUN USING A RAMP VOLUME EQUAL TO THE,
     41X,33HOBSERVED RAMP VOLUME OF THIS RUN.)
  898 GO TO 500
```

```
C     BEGIN SIMULATION OF 1000 VEHICLES FOR OBSERVATION
C     CALL IN 2 RANDOM NUMBERS TO SAMPLE RAMP HEADWAY DIST.

  900 GO TO (901,903,905,907,909),NOSIMS
  901 RRDNO1 = RRAND1(DUMMY)
  902 RRDNO2 = RRAND1(DUMMY)
      GO TO 915
  903 RRDNO1 = RRAND2(DUMMY)
  904 RRDNO2 = RRAND2(DUMMY)
      GO TO 915
  905 RRDNO1 = RRAND3(DUMMY)
  906 RRDNO2 = RRAND3(DUMMY)
      GO TO 915
  907 RRDNO1 = RRAND4(DUMMY)
  908 RRDNO2 = RRAND4(DUMMY)
      GO TO 915
  909 RRDNO1 = RRAND5(DUMMY)
  910 RRDNO2 = RRAND5(DUMMY)

C     GENERATE NEXT RAMP HEADWAY
  915 RH = RAMP(RRDNO1,RRDNO2,RA1,RT1,RD1,RA2,RT2,RD2)
C     INCREMENT TOTAL RAMP VEHICLE COUNTER
  916 I=I+1
C     INCREMENT OBSERVED RAMP VEHICLE COUNTER
  917 L = L + 1
C     CALCULATE RAMP ARRIVAL TIME
    1 RAT(I) = RAT(I-1)+RH
C     CALCULATE DEPARTURE TIME IF RAMP VEHICLE ACCELERATED
C     IMMEDIATELY UPON ARRIVAL INTO SYSTEM
    2 RDT(I) = RAT(I)+C1TIME
C     CALCULATE EARLIEST POSSIBLE DEPARTURE TIME WITHOUT
C     OVERTAKING LEADING RAMP VEHICLE
    3 EDEPTM = RDT(I-1)+1.8
C     DETERMINE IF QUEUE EXISTS
    4 IF(RDT(I)-RDT(I-1))80,6,6
    6 IQ=1
C     NO QUEUE EXISTS
C     DETERMINE OPERATING CHARACTERISTICS WHILE IN SYSTEM
 1116 IF(RDT(I)-EDEPTM)7,3117,3117
    7 IC=2

C     NO DECELERATION, BUT DELAYED ACCELERATION
C     CALCULATE RAMP DEPARTURE TIME ASSUMING VEHICLE IN
C     QUESTION WILL FOLLOW A LEADING VEHICLE AT
C     A MINIMUM HEADWAY
 1117 RDT(I) = RDT(I-1)+1.8
 2117 GO TO 8
 3117 IC=1
```

```
C     IMMEDIATE ACCELERATION
C     INCREMENT NON-RESTRICTED VEHICLE COUNTER
    8 J=J+1

C     ENTER QUEUE LENGTH IN QUEUE LENGTH SUMMARY
    9 LQ(L)=0

C     DETERMINE IF LAG EXISTS IN SHOULDER LANE
C     IF ONE DOES, GO AHEAD TO DETERMINE LENGTH.  IF NO LAG
C     EXISTS, GENERATE A GAP.
   12 IF(RDT(I)-SAT2)36,14,14
C     CALL IN RANDOM NUMBER TO SAMPLE
C     SHOULDER LANE HEADWAY DISTRIBUTION
   14 GO TO (16,18,20,22,24),NOSIMS
   16 SRDNO=SRAND1(DUMMY)
   17 GO TO 26
   18 SRDNO=SRAND2(DUMMY)
   19 GO TO 26
   20 SRDNO=SRAND3(DUMMY)
   21 GO TO 26
   22 SRDNO=SRAND4(DUMMY)
   23 GO TO 26
   24 SRDNO=SRAND5(DUMMY)

C     GENERATE NEXT SHOULDER LANE HEADWAY
   26 SH=SHLANE(SRDNO, SHLVOL, D, Z)
C     UP-DATE SHOULDER-LANE ARRIVAL TIMES
   28 SAT1=SAT2
   30 SAT2=SAT2+SH

C     INCREMENT SHOULDER-LANE VOLUME COUNTER
   32 NSVEH=NSVEH+1
   34 GO TO 12

C     CALCULATE LENGTH OF AVAILABLE GAP
   36 ASG = SAT2-RDT(I)
C     CALL IN RANDOM NUMBER TO SAMPLE ACCEPTANCE
C     DISTRIBUTION
   37 ARDNO=ARAND(DUMMY)

C     DETERMINE IF GAP IS ACCEPTABLE AFTER SELECTING THE
C     PROPER DECISION MODEL DEPENDENT UPON THE
C     OPERATING CONDITION
C     IF GAP IS ACCEPTABLE, PROCEED AHEAD TO UPDATE RAMP
C     VOLUME COUNTER.  IF NOT CALCULATE NEW POSSIBLE
C     DEPARTURE TIME
   38 GO TO (39,39,39,41,39),IC
   39 CALL ACPT1(ASG,ARDNO,A1,B1,ACPTNO)
   40 GO TO 42
   41 CALL ACPT2(ASG,ARDNO,A2,B2,ACPTNO)
   42 IF(ACPTNO)53,53,43
   43 RDT(I) = SAT2+0.5
```

```
C       DETERMINE AMOUNT OF AVAILABLE TIME TO EARLIEST
C       DEPARTURE TIME AND THE RESULTING OPERATING
C       CHARACTERISTICS.
     44 AVLTIM = RDT(I)-RAT(I)
     45 IF(AVLTIM-C2TIME)46,46,48
     46 IC=2
C       NO DECELERATION, BUT DELAYED ACCELERATION
     47 GO TO 14
     48 IF(AVLTIM-C3TIME)49,49,51
     49 IC=3

C       DECELERATION, FOLLOWED BY ACCELERATION WITHOUT A STOP
     50 GO TO 14
     51 IC=4
C       DECELERATION TO STOP.  VEHICLE LEAVES FROM
C       1ST-IN-LINE POSITION
     52 GO TO 14
C       INCREMENT RAMP VOLUME COUNTER
     53 NRDEPT = NRDEPT+1
C       UP-DATE QUEUE-OPERATING CONDITION
     54 GO TO (55,100),IQ
     55 GO TO (56,58,60,62),IC
     56 NQ1IC1 = NQ1IC1+1
     57 GO TO 204
     58 NQ1IC2 = NQ1IC2+1
     59 GO TO 204
     60 NQ1IC3 = NQ1IC3+1
     61 GO TO 204
     62 NQ1IC4 = NQ1IC4+1

C       UP-DATE WAIT-TIME, SERVICE-TIME, SYSTEM-TIME AND
C       DELAY-TIME SUMMARIES
    204 WAIT(L) = 0.
    205 SRTIM1(J) = RDT(I)-(RAT(I)+C1TIME)
    206 ASRTM1=ASRTM1+SRTIM1(J)
    207 ASSRT1=ASSRT1+SRTIM1(J)**2.
    208 SRTIM(L) = SRTIM1(J)
    209 ASRTIM = ASRTIM + SRTIM(L)
    210 ASSRTM = ASSRTM + SRTIM(L)**2.
    211 SYSTM1(J) = RDT(I)-(RAT(I)+C1TIME)
    212 ASYTM1 = ASYTM1+SYSTM1(J)
    213 ASSYT1 = ASSYT1+SYSTM1(J)**2.
    214 SYSTIM(L) = SYSTM1(J)
    215 ASYTM = ASYTM+SYSTIM(L)
    216 ASSYTM = ASSYTM + SYSTIM(L)**2.
    217 SYSTM = SYSTM1(J)
    218 GO TO 240
     80 IQ=2
```

```
C      QUEUE EXISTS

C      INCREMENT RESTRICTED VEHICLE COUNTER
   81 K=K+1

C      DETERMINE AMOUNT OF AVAILABLE TIME TO EARLIEST
C      DEPARTURE TIME
   82 AVLTIM = EDEPTM-RAT(I)

C      DETERMINE QUEUE LENGTH

   83 QITIME = RAT(I)+C1TIME
   84 DO 87 IQL1=1,1300,1
   85 IQL2 = I-IQL1
   86 IF(QITIME-RDT(IQL2))87,87,88
   87 CONTINUE

C      ENTER QUEUE LENGTH IN QUEUE LENGTH SUMMARY
   88 LQ(L) = IQL1-1

C      ACCUMULATE SUM OF QUEUE LENGTHS
   89 W = IQL1-1
   90 WQL = WQL+W

C      DETERMINE OPERATING CHARACTERISTICS
   91 IF(AVLTIM-C2TIME)92,92,94
   92 IC=2

C      NO DECELERATION, BUT DELAYED ACCELERATION
   93 GO TO 98
   94 IF(AVLTIM-C3TIME)95,95,97
   95 IC=3

C      DECELERATION, FOLLOWED BY ACCELERATION WITHOUT A STOP
   96 GO TO 98
   97 IC=5

C      DECELERATION TO STOP.  VEHICLE LEAVES FROM
C      NTH-IN-LINE POSITION

C      DETERMINE NEW POSSIBLE RAMP DEPARTURE TIME
   98 RDT(I) = RDT(I-1)+1.8
   99 GO TO 12

C      UP-DATE QUEUE-OPERATING CONDITION COUNTERS
  100 GO TO (102,102,104,106,108),IC
  102 NQ21C2=NQ21C2+1
```

```
  103 GO TO 220
  104 NQ2IC3=NQ2IC3+1
  105 GO TO 220
  106 NQ2IC4=NQ2IC4+1
  107 GO TO 220
  108 NQ2IC5=NQ2IC5+1

C     UP-DATE WAIT-TIME, SERVICE-TIME, SYSTEM-TIME AND
C     DELAY-TIME SUMMARIES

  220 WAIT2(K) = RDT(I-1)-(RAT(I)+C1TIME)
  221 AWAIT2 = AWAIT2+WAIT2(K)
  222 ASWT2=ASWT2+WAIT2(K)**2.
  223 WAIT(L) = WAIT2(K)
  224 AWAIT = AWAIT + WAIT(L)
  225 ASWAIT = ASWAIT + WAIT(L)**2.
  226 SRTIM2(K) = RDT(I)-RDT(I-1)
  227 ASRTM2=ASRTM2+SRTIM2(K)
  228 ASSRT2=ASSRT2+SRTIM2(K)**2.
  229 SRTIM(L) = SRTIM2(K)
  230 ASRTIM = ASRTIM + SRTIM(L)
  231 ASSRTM = ASSRTM + SRTIM(L)**2.
  232 SYSTM2(K) = RDT(I) - (RAT(I)+C1TIME)
  233 ASYTM2=ASYTM2+SYSTM2(K)
  234 ASSYT2=ASSYT2+SYSTM2(K)**2.
  235 SYSTIM(L) = SYSTM2(K)
  236 ASYTM = ASYTM + SYSTIM(L)
  237 ASSYTM = ASSYTM + SYSTIM(L)**2.
  238 SYSTM=SYSTM2(K)

C     INCREMENT DELAY-PERIOD COUNTERS
  240 CALL NVWGT(DELAY,NVW30,NVW60,
     1NVW90,NVW120,NVW150,NVW180)

C     UP-DATE TIME CLOCK
  250 TIME=RDT(I)/3600.

C     DETERMINE IF SIMULATION TIME LIMIT IS EXCEEDED
  255 IF(TIME-TIMMAX)260,515,515

C     DETERMINE IF TOTAL SAMPLE HAS BEEN OBSERVED
  260 IF(NRDEPT-1300)900,264,264
```

```
C     CALCULATE PERCENTAGES BY LENGTH OF DELAY

  264 XVW30 = NVW30
      PVW30 = (XVW30/1000.)

  265 XVW60 = NVW60
      PVW60 = (XVW60/1000.)

  266 XVW90 = NVW90
      PVW90 = (XVW90/1000.)

  267 XVW120 = NVW120
      PVW120 = (XVW120/1000.)

  268 XVW150 = NVW150
      PVW150 = (XVW150/1000.)

  269 XVW180 = NVW180
      PVW180 = (XVW180/1000.)

C     CALCULATE NUMBERS OF RESTRICTED
C     AND NON-RESTRICTED VEHICLES

  270 XK=K
  271 XJ=J

C     CALCULATE MEANS, VARIANCES AND STANDARD DEVIATIONS
C     OF WAIT-TIMES, SERVICE-TIMES, AND SYSTEM-TIMES

  272 AVWT1=0.
  273 VRWT1=0.
  274 SDWT1=0.
  275 AVWT2=AWAIT2/XK
  276 VRWT2=(ASWT2-(AWAIT2**2.)/XK)/(XK-1.)
  277 SDWT2=SQRT(VRWT2)
  278 AVWAIT=AWAIT/1000.
  279 VRWAIT=(ASWAIT-(AWAIT**2.)/1000.)/999.
  280 SDWAIT=SQRT(VRWAIT)
  281 AVSRT1=ASRTM1/XJ
  282 VRSRT1=(ASSRT1-(ASRTM1**2.)/XJ)/(XJ-1.)
  283 SDSRT1=SQRT(VRSRT1)
  284 AVSRT2=ASRTM2/XK
  285 VRSRT2=(ASSRT2-(ASRTM2**2.)/XK)/(XK-1.)
  286 SDSRT2=SQRT(VRSRT2)
```

```
287 AVSRT=ASRTIM/1000.
288 VRSRT = (ASSRTM-(ASRTIM**2.)/1000.)/999.
289 SDSRT=SQRT(VRSRT)
290 AVSYT1 = ASYTM1/XJ
291 VRSYT1 = (ASSYT1-(ASYTM1**2.)/XJ)/(XJ-1.)
292 SDSYT1 = SQRT(VRSYT1)
293 AVSYT2=ASYTM2/XK
294 VRSYT2=(ASSYT2-(ASYTM2**2.)/XK)/(XK-1.)
295 SDSYT2=SQRT(VRSYT2)
296 AVSYT=ASYTM/1000.
297 VRSYT=(ASSYTM-(ASYTM**2.)/1000.)/999.
298 SDSYT=SQRT(VRSYT)
299 XI=1000.

C     SORT WAIT-TIME, SERVICE-TIME, SYSTEM-TIME, AND
C     QUEUE-LENGTH DISTRIBUTIONS INTO AN INCREASING ORDER

305 CALL SORT1(J,SRTIM1)
306 CALL SORT1(J,SYSTM1)
307 CALL SORT1(K,WAIT2)
308 CALL SORT1(K,SRTIM2)
309 CALL SORT1(K,SYSTM2)
311 CALL SORT1(1000,SRTIM)
312 CALL SORT1(1000,SYSTIM)
313 CALL SORT2(LQ)

C     CALCULATE SIMULATED RAMP AND SHOULDER-LANE VOLUMES

330 XNSVEH=NSVEH
332 SHLVPH = (XNSVEH/SAT2)*3600.
336 RAMVPH = (1000./(RAT(1300)-RAT(300)))*3600.
341 NVW=XK

C     CALCULATE AVERAGE, MAXIMUM, AND VARIOUS PERCENTILE
C     QUEUE LENGTHS

344 AVQL=WQL/1000.
345 P85=LQ(850)
346 P90=LQ(900)
347 P95=LQ(950)
350 LQMAX = LQ(1000)
```

```
C     WRITE OUTPUT FROM SIMULATION RUN

  400 WRITE(6,401)
  401 FORMAT(1H1,37X,
     144HRAMP CAPACITY ANALYSIS BY DIGITAL SIMULATION,/
     244X,31HACCELERATION LANE -- NO CONTROL, / )

  402 WRITE (6, 403) NSVEH, SHLVPH, NRDEPT, RAMVPH, TIME
  403 FORMAT(/ 1H0,54X,12HTRAFFIC DATA, //
     113X,6HNUMBER,5X,2HOF,9X,13HSHOULDER LANE,11X,6HNUMBER,
     211X,13HRAMP   VOLUME,9X,10HSIMULATION,/
     313X,13HSHOULDER LANE,12X,6HVOLUME,14X,8HOF  RAMP,/
     415X,8HVEHICLES,12X,13HVEH. PER HOUR,10X,8HVEHICLES,
     510X,13HVEH. PER HOUR,9X,10HTIME (HRS),//
     616X,I5,18X,F6.0,16X,I4,16X,F5.0,12X,F8.4,/)

  404 WRITE (6,406)J,AVQL, P85,P90, P95, LQMAX
  406 FORMAT(/ 1H0,47X,23HQUEUING CHARACTERISTICS,//
     113X,11HNUMBER   OF,4X,11HAVG. LENGTH,5X,
     213H85 TH PERCENT,4X,13H90 TH PERCENT,5X,
     313H95 TH PERCENT,7X,7HMAXIMUM,/
     413X,11HZERO QUEUES,4X,11HOF    QUEUE,5X,
     513HQUEUE  LENGTH,4X,13HQUEUE  LENGTH,5X,
     613HQUEUE  LENGTH,4X,12HQUEUE LENGTH,//
     717X,I3,9X,F5.2,12X,F5.0,12X,F5.0,13X,F5.0,13X,I4,/)

  408 WRITE(6,410)
  410 FORMAT(/1H0,48X,22HDELAY  CHARACTERISTICS  )

  412 WRITE(6,414)PVW30,PVW60,PVW90,PVW120,PVW150,PVW180
  414 FORMAT(1H0,12X,
     151HP R O B A B I L I T Y      T H A T      D E L A Y,
     27X,37HI S     G R E A T E R      T H A N,/
     313X,10H30-SECONDS,7X,10H60-SECONDS,7X,10H90-SECONDS,
     46X,11H120-SECONDS,6X,11H150-SECONDS,6X,
     511H180-SECONDS,//3X,6F17.3,/)

  415 WRITE(6,1415) C1TIME,C2TIME,C3TIME
 1415 FORMAT( / ,1H0,12X,21HSYSTEM TIME CONSTANTS, //
     113X,22HTIME  FOR  IMMEDIATE,19X,
     222HTIME  FOR  EXACTLY  NO,18X,14HTIME FOR EXACT, /
     313X,22HACCELERATION CONDITION,19X,
     422HDECELERATION CONDITION,18X,14HSTOP CONDITION, //
     521X,F6.2,35X,F6.2,30X,F6.2)
```

```
 419 WRITE(6,1419) NQ1IC1,NQ1IC2,NQ1IC3,NQ1IC4,
    1NQ2IC2,NQ2IC3,NQ2IC4,NQ2IC5)

1419 FORMAT(/ 1HO,12X,
    143HNUMBERS OF VEHICLES BY OPERATING CONDITIONS, //
    230X,8HNO QUEUE,21X,3H+++,22X,5HQUEUE,  /
    310X,9HIMMEDIATE,5X,7HDELAYED,4X,12HDECELERATION,5X,
    44HSTOP,7X,7HDELAYED,4X,12HDECELERATION,2X,
    510HSTOP VEH 1,3X,10HSTOP VEH N,   /
    69X,12HACCELERATION,1X,12HACCELERATION,1X,
    712HACCELERATION,1X,12HACCELERATION,1X,
    812HACCELERATION,1X,12HACCELERATION,1X,
    912HACCELERATION,1X,12HACCELERATION, //  3X,8I13)

 416 WRITE (6,418) NVW, J, AVWAIT, AVWT2, VRWT2, SDWT2

 418 FORMAT(/1HO,12X,14HWAIT TIME DATA,//
    113X,8HNO.   OF,7X,6HNO. OF,7X,9HAVG. WAIT,8X,
    212HAVG.    WAIT,7X,12HVAR. OF WAIT,7X,12HSTD. DEV. OF/
    313X,8HVEHICLES,8X,4HZERO,8X,9HFOR   ALL,8X,
    412HFOR VEHICLES,7X,12HFOR VEHICLES 7X,12HWAIT FOR VEH/
    513X,7HWAITING,8X,5HWAITS,8X,8HVEHICLES,9X,
    612HTHAT    WAIT,7X,12HTHAT    WAIT,7X,12HTHAT    WAIT,
    7//15X,I3,11X,I3,10X,F7.2,11X,F7.2,13X,F6.2,13X,F6.2/)

 420 WRITE(6,401)

 422 WRITE(6,410)

 424 WRITE(6,426)

 426 FORMAT(1HO,12X,34HSERVICE TIME   (ZERO WAIT VEHICLES))

 428 WRITE(6,430)XJ,AVSRT1,VRSRT1,SDSRT1

 430 FORMAT(1HO,13X,6HNUMBER,22X,7HAVERAGE,
    121X,8HVARIANCE,21X,9HSTD. DEV.,/
    216X,2HOF,24X,7HSERVICE,21X,7HSERVICE,23X,7HSERVICE,/
    313X,8HVEHICLES,22X,4HTIME,25X,4HTIME,25X,4HTIME,//
    414X,F5.0,23X,F7.2,22X,F7.2,23X,F7.2,/)

 431 FORMAT(1HO,13X,6HNUMBER,22X,7HAVERAGE,
    121X,8HVARIANCE,21X,9HSTD. DEV.,/
    216X,2HOF,24X,6HSYSTEM,22X,6HSYSTEM,24X,6HSYSTEM, /
    313X,8HVEHICLES,22X,4HTIME,25X,4HTIME,25X,4HTIME,//
    414X,F5.0,23X,F7.2,22X,F7.2,23X,F7.2,/)
```

```
432 WRITE(6,434)

434 FORMAT(/1HO,12X,32HSERVICE TIME  (WAITING VEHICLES))

436 WRITE(6,430)XK,AVSRT2,VRSRT2,SDSRT2

438 WRITE(6,440)
440 FORMAT(/1HO,12X,28HSERVICE TIME  (ALL VEHICLES))

442 WRITE(6,430)XI,AVSRT,VRSRT,SDSRT
444 WRITE(6,446)
446 FORMAT(/1HO,12X,33HSYSTEM TIME  (ZERO WAIT VEHICLES))

448 WRITE(6,431)XJ,AVSYT1,VRSYT1,SDSYT1
450 WRITE(6,452)
452 FORMAT(/1HO,12X,31HSYSTEM TIME  (WAITING VEHICLES))

454 WRITE(6,431)XK,AVSYT2,VRSYT2,SDSYT2
456 WRITE(6,458)
458 FORMAT(/1HO,12X,27HSYSTEM TIME  (ALL VEHICLES))

460 WRITE(6,431)XI,AVSYT,VRSYT,SDSYT
462 WRITE (6,464)
464 FORMAT(1H1,9X,5HINDEX,5X,4HWAIT,6X,7HSERVICE,5X,
   16HSYSTEM,5X,7HSERVICE,5X,6HSYSTEM,5X,5HTOTAL,8X,
   25HTOTAL,8X,5HQUEUE,/11X,3HFOR,6X,5HGIVEN,6X,5HGIVEN,
   36X,5HGIVEN,8X,4HZERO,7X,
   44HZERO,5X,7HSERVICE,6X,6HSYSTEM,7X,6HLENGTH, /
   510X,5HDIST.,5X,4HWAIT,7X,4HWAIT,8X,4HWAIT,8X,4HWAIT,
   67X,4HWAIT,7X,4HTIME,8X,4HTIME,8X,7HSUMMARY )

465 DO 466 I=1,1000,1
466 WRITE(6,468) I,WAIT2(I),SRTIM2(I),SYSTM2(I),SRTIM1(I),
   1SYSTM1(I),SRTIM(I),SYSTIM(I),LQ(I)
468 FORMAT(10X,I4,2F11.2,2F12.2,2F11.2,F12.2,8X,I4)

470 WRITE(6,472) RAMVOL, RA1,RT1, RD1, RA2, RT2, RD2
472 FORMAT(1H1,16X,4HRAMP,7X,7HPORTION,6X,9HAVG. FREE,
   16X,9HMIN. FREE,8X,7HPORTION,7X,9HAVG.RES.,6X,
   29HMIN. RES.,/15X,6HVOLUME,7X,4HFREE,9X,7HHEADWAY,8X,
   37HHEADWAY,7X,10HRESTRAINED,7X,7HHEADWAY,8X,7HHEADWAY,/
   416X,F5.0,7X,F4.2,10X,F5.2,10X,F4.2,12X,F4.2,11X,F5.2,
   510X,F5.2)

500 CONTINUE
510 STOP
```

```
C     CALCULATIONS FOR OUTPUT WHEN TIME LIMIT IS EXCEEDED
  515 XNSVEH = NSVEH
  516 SHLVPH = 3600.*XNSVEH/SAT2
  517 XNRDEP = NRDEPT
  518 RAMVPH = 3600.*((XNRDEP-300.)/(RDT(I)-RDT(300)))
C     OUTPUT WHEN TIME LIMIT IS EXCEEDED
  519 WRITE(6,401)
  520 WRITE(6,403) NSVEH,SHLVPH,NRDEPT,RAMVPH,TIME
  525 WRITE(6,530)
  530 FORMAT(1H0,/////,13X,
     148HSIMULATION RUN TERMINATED DUE TO TIME LIMITATION)
  535 STOP
      END
C     SUBROUTINE TO DETERMINE IF A GAP OF A GIVEN LENGTH
C     IS ACCEPTABLE TO A MOVING RAMP VEHICLE
$IBFTC ACPT1
      SUBROUTINE ACPT1(ASG,ARDNO,A1,B1,ACPTNO)
    1 IF(ASG-4.00)5,30,30
    5 IF(ASG-1.00)10,10,20
   10 PAG = 0.
   15 GO TO 35
   20 PAG = A1*ALOG(ASG)-A1*B1
   25 GO TO 35
   30 PAG = 1.0
   35 ACPTNO = ARDNO-PAG
   40 RETURN
      END


C     SUBROUTINE TO DETERMINE IF A GAP OF A GIVEN LENGTH
C     IS ACCEPTABLE TO A STOPPED FIRST IN LINE RAMP VEHICLE
$IBFTC ACPT2
      SUBROUTINE ACPT2(ASG,ARDNO,A2,B2,ACPTNO)
    1 IF(ASG-8.00)5,30,30
    5 IF(ASG-2.50)10,10,20
   10 PAG = 0.
   15 GO TO 35
   20 PAG = A2*ALOG(ASG)-A2*B2
   25 GO TO 35
   30 PAG = 1.
   35 ACPTNO = ARDNO-PAG
   40 RETURN
      END
C
C     THE REMAINDER OF THE PROGRAM IS COMMON TO THE STOP-SIGN,
C     YIELD-SIGN, AND ACCELERATION-LANE SIMULATORS AND IS
C     GIVEN IN APPENDIX B.4
```

APPENDIX B.4

```
C      SUBROUTINES COMMON TO THE STOP-SIGN, YIELD-SIGN, AND
C      ACCELERATION-LANE SIMULATORS
.
C      SUBROUTINE TO SOLVE FOR HYPER-EXPONENTIAL HEADWAY
C      MODEL PARAMETERS USING KELL'S STATISTICAL ESTIMATORS

$IBFTC RPDATA
      SUBROUTINE RPDATA(RAMVOL, RA1,RT1, RD1, RA2, RT2, RD2)
      C1=4827.9/(RAMVOL**1.024)
      A=-0.046 - 0.0448*(RAMVOL/100.)
      C2=2.659-0.120*(RAMVOL/100.)
      C=(EXP(-10.503 + 2.829*ALOG(RAMVOL)
     1-0.173*(ALOG(RAMVOL))**2.))-2.
      RD1=1.00
      RA1=EXP(A-RD1/C1)
      IF (RA1-1.0)10,5,5
    5 RA1=1.0
      RA2=0.0
      RD2=RD1
      RT1=3600./RAMVOL
      RT2=RT1
      GO TO 40
   10 IF(RA1-0.)15, 15, 20
   15 RA1=0.0
      RA2=1.0
      RD2=C2*(C-ALOG(RA2))
      RD1=RD2
      RT2=3600./RAMVOL
      RT1=RT2
      GO TO 40
   20 RA2=1.0-RA1
   25 RD2=C2*(C-ALOG(RA2))
   30 RT1=C1 + RD1
   35 RT2=C2 + RD2
   40 RETURN
      END
```

```
C     SUBROUTINE TO SOLVE FOR PARAMETERS OF
C     SHIFTED EXPONENTIAL HEADWAY MODEL


$IBFTC SHDATA
      SUBROUTINE SHDATA(SHLVOL, D, Z)
      D=0.30 + SHLVOL/10000.
      T=3600./SHLVOL
      Z=-(T-D)
      RETURN
      END



C     SUBROUTINE TO GENERATE RAMP HEADWAYS


$IBFTC RAMP
      FUNCTION RAMP(RRDNO1,RRDNO2,RA1,RT1,RD1,RA2,RT2,RD2)
      IF(RRDNO1-RA1)1,1,2
    1 RAMP = -(RT1-RD1)*ALOG(RRDNO2)+RD1
      GO TO 3
    2 RAMP = -(RT2-RD2)*ALOG(RRDNO2)*RD2
    3 RETURN
      END



C     SUBROUTINE TO GENERATE SHOULDER-LANE HEADWAYS


$IBFTC SHLANE
      FUNCTION SHLANE(SRDNO,SHLVOL,D,Z)
      SHLANE = Z*ALOG(1.-SRDNO) + D
      RETURN
      END
```

```
C     SUBROUTINE TO INCREMENT DELAY-PERIOD COUNTERS

$IBFTC NVWGT
      SUBROUTINE NVWGT(SYSTIM,NVW30,NVW60,NVW90,NVW120,
     1NVW150,NVW180)
    1 IF(SYSTIM-180.)4,2,2
    2 NVW180 = NVW180+1
    3 GO TO 5
    4 IF(SYSTIM-150.)7,5,5
    5 NVW150=NVW150+1
    6 GO TO 8
    7 IF(SYSTIM-120.)10,8,8
    8 NVW120=NVW120+1
    9 GO TO 11
   10 IF(SYSTIM-90.)13,11,11
   11 NVW90=NVW90+1
   12 GO TO 14
   13 IF(SYSTIM-60.)16,14,14
   14 NVW60=NVW60+1
   15 GO TO 17
   16 IF(SYSTIM-30.)18,17,17
   17 NVW30=NVW30+1
   18 RETURN
      END
```

```
C     SUBROUTINE TO SORT FLOATING POINT QUANTITIES

$IBFTC SORT1
      SUBROUTINE SORT1(N,X)
      DIMENSION X(1000)
      MAX1 = N-1
    1 DO 7 I=1,MAX1,1
      MIN1 = I+1
    2 DO 7 J=MIN1,N,1
    3 IF(X(I)-X(J))7,7,4
    4 TEMP=X(I)
    5 X(I)=X(J)
    6 X(J)=TEMP
    7 CONTINUE
    8 IF(N-1000)9,15,15
    9 MIN2 = N+1
      DO 10 I=MIN2,1000,1
   10 X(I)=9999.9999
   15 RETURN
      END
```

```
C     SUBROUTINE TO SORT FIXED POINT QUANTITIES

$IBFTC SORT2
      SUBROUTINE SORT2(L)
      DIMENSION L(1000)
    1 DO 7 I=1,999,1
      MIN = I+1
    2 DO 7 J=MIN,1000,1
    3 IF(L(I)-L(J))7,7,4
    4 LOCAL=L(I)
    5 L(I)=L(J)
    6 L(J)=LOCAL
    7 CONTINUE
   10 RETURN
      END
```

```
C     SUBROUTINE TO GENERATE RANDOM NUMBERS TO SAMPLE
C     GAP ACCEPTANCE DISTRIBUTIONS


$IBMAP ARNDM   40
       REM     NYU UNIFORM RANDOM NUMBER GENERATOR.
       REM
       REM          THIS GENERATOR HAS BEEN CODED AS A MAP
       REM     ROUTINE FOR USE WITH A MAIN PROGRAM CODED IN
       REM     THE FORTRAN IV LANGUAGE.  ARDNO = ARAND(DUMMY)
       REM     SETS ARDNO EQUAL TO THE NEXT RANDOM NUMBER.
       REM     DUMMY IS A DUMMY ARGUMENT USED TO SATISFY THE
       REM     FORTRAN IV REQUIREMENT THAT ALL FUNCTIONS
       REM     HAVE AT LEAST ONE ARGUMENT.
       REM
       REM     METHOD OF GENERATION.
       REM          A*R**N IS COMPUTED FOR N = 1, 2, 3, ....
       REM     ...2**27, WHERE A IS ANY ODD NUMBER AND R IS
       REM     A RANDOM NUMBER OF THE FORM 8*K+5 -- K BEING
       REM     ANY INTEGER.  AFTER MULTIPLICATION AT EACH
       REM     LEVEL OF N, ALL EXCEPT THE 30 LOWEST ORDER
       REM     BITS ARE DROPPED.  FROM EACH 30 LOW-ORDER BIT
       REM     PORTION OF A*R**N, THE 27 HIGHEST ORDER BITS
       REM     ARE USED TO FORM THE NEXT RANDOM NUMBER, AND
       REM     ARE CONVERTED TO FLOATING POINT FORM.  THE
       REM     RESULTING DISTRIBUTION OF RANDOM NUMBERS IS
       REM     UNIFORM OVER THE INTERVAL (0,1), AND THE SEQ-
       REM     UENCE DOES NOT REPEAT UNTIL 2**27 RANDOM NUM-
       REM     BERS HAVE BEEN GENERATED.  THE APPROXIMATE
       REM     TIME FOR GENERATION IS 75 MICROSECONDS.
ARAND  SAVE
       LDQ     RANDNO
       MPY     FACTOR
       LLS     5
       ZAC                         ZERO ACCUMULATOR
       LRS     5
       STQ     RANDNO
       LLS     32
       ORA     MASK
       FAD     MASK
       RETURN  ARAND
RANDNO OCT     005343277245
FACTOR OCT     005343277245
MASK   OCT     200000000000
       END
```

```
C       FIVE SUBROUTINES TO GENERATE RANDOM NUMBERS
C       TO SAMPLE RAMP HEADWAY DISTRIBUTION

$IBMAP RRNDM1  25
RRAND1 SAVE
       LDQ     RANDNO
       MPY     FACTOR
       LLS     5
       ZAC                       ZERO ACCUMULATOR
       LRS     5
       STQ     RANDNO
       LLS     32
       ORA     MASK
       FAD     MASK
       RETURN  RRAND1
RANDNO OCT     005343277245
FACTOR OCT     005343277245
MASK   OCT     200000000000
       END
$IBMAP RRNDM2  25
RRAND2 SAVE
       LDQ     RANDNO
       MPY     FACTOR
       LLS     5
       ZAC                       ZERO ACCUMULATOR
       LRS     5
       STQ     RANDNO
       LLS     32
       ORA     MASK
       FAD     MASK
       RETURN  RRAND2
RANDNO OCT     005343277245
FACTOR OCT     005343277245
MASK   OCT     200000000000
       END
$IBMAP RRNDM3  25
RRAND3 SAVE
       LDQ     RANDNO
       MPY     FACTOR
       LLS     5
       ZAC                       ZERO ACCUMULATOR
       LRS     5
       STQ     RANDNO
       LLS     32
       ORA     MASK
       FAD     MASK
       RETURN  RRAND3
RANDNO OCT     005343277245
FACTOR OCT     005343277245
MASK   OCT     200000000000
       END
```

```
$IBMAP RRNDM4   25
RRAND4 SAVE
       LDQ      RANDNO
       MPY      FACTOR
       LLS      5
       ZAC                          ZERO ACCUMULATOR
       LRS      5
       STQ      RANDNO
       LLS      32
       ORA      MASK
       FAD      MASK
       RETURN   RRAND4
RANDNO OCT      005343277245
FACTOR OCT      005343277245
MASK   OCT      200000000000
       END
```

```
$IBMAP RRNDM5   25
RRAND5 SAVE
       LDQ      RANDNO
       MPY      FACTOR
       LLS      5
       ZAC                          ZERO ACCUMULATOR
       LRS      5
       STQ      RANDNO
       LLS      32
       ORA      MASK
       FAD      MASK
       RETURN   RRAND5
RANDNO OCT      005343277245
FACTOR OCT      005343277245
MASK   OCT      200000000000
       END
```

```
C       FIVE SUBROUTINES TO GENERATE RANDOM NUMBERS
C       TO SAMPLE SHOULDER-LANE HEADWAY DISTRIBUTION

$IBMAP SRNDM1  25
SRAND1 SAVE
       LDQ     RANDNO
       MPY     FACTOR
       LLS     5
       ZAC                        ZERO ACCUMULATOR
       LRS     5
       STQ     RANDNO
       LLS     32
       ORA     MASK
       FAD     MASK
       RETURN  SRAND1
RANDNO OCT     005343277245
FACTOR OCT     005343277245
MASK   OCT     200000000000
       END
$IBMAP SRNDM2  25
SRAND2 SAVE
       LDQ     RANDNO
       MPY     FACTOR
       LLS     5
       ZAC                        ZERO ACCUMULATOR
       LRS     5
       STQ     RANDNO
       LLS     32
       ORA     MASK
       FAD     MASK
       RETURN  SRAND2
RANDNO OCT     005343277245
FACTOR OCT     005343277245
MASK   OCT     200000000000
       END
$IBMAP SRNDM3  25
SRAND3 SAVE
       LDQ     RANDNO
       MPY     FACTOR
       LLS     5
       ZAC                        ZERO ACCUMULATOR
       LRS     5
       STQ     RANDNO
       LLS     32
       ORA     MASK
       FAD     MASK
       RETURN  SRAND3
RANDNO OCT     005343277245
FACTOR OCT     005343277245
MASK   OCT     200000000000
       END
```

```
$IBMAP SRNDM4  25
SRAND4 SAVE
       LDQ     RANDNO
       MPY     FACTOR
       LLS     5
       ZAC                     ZERO ACCUMULATOR
       LRS     5
       STQ     RANDNO
       LLS     32
       ORA     MASK
       FAD     MASK
       RETURN  SRAND4
RANDNO OCT     005343277245
FACTOR OCT     005343277245
MASK   OCT     200000000000
       END
```

```
$IBMAP SRNDM5  25
SRAND5 SAVE
       LDQ     RANDNO
       MPY     FACTOR
       LLS     5
       ZAC                     ZERO ACCUMULATOR
       LRS     5
       STQ     RANDNO
       LLS     32
       ORA     MASK
       FAD     MASK
       RETURN  SRAND5
RANDNO OCT     005343277245
FACTOR OCT     005344277245
MASK   OCT     200000000000
       END
```

VITA

VITA

Robert Frank Dawson was born April 16, 1935, in Vergennes, Vermont. He received his primary education in Burlington, Vermont, and was graduated from the Burlington High School in 1953.

He received the Bachelor of Science in Civil Engineering degree from the University of Vermont in 1957; a Certificate in Highway Traffic Engineering from Yale University in 1960; and the Master of Science in Civil Engineering degree from Cornell University in 1961.

From 1957 to 1958 he served as an Ensign in the United States Navy.

In 1960 he was appointed to the staff of the University of Oklahoma as an instructor in the School of Civil Engineering, which position he resigned in 1962 to undertake additional graduate study at Purdue University.

He is a member of the Tau Beta Pi engineering honorary society, a member of Sigma Xi research honorary, an associate member of the American Society of Civil Engineers, a junior member of the Institute of Traffic Engineers, and an associate member of the Highway Research Board.